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CROSS-DOMAIN NETWORK CONNECTIVITY

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THESIS

CROSS-DOMAIN NETWORK CONNECTIVITY

by

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March 2017

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CROSS-DOMAIN NETWORK CONNECTIVITY

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Connectivity among two or more communication nodes forms the basic network for cross-domain information exchange. The communication nodes that represent actual operational scenarios are identified, and the efficiency of a proposed multi-tier network is examined by performing link budget analysis and simulation to determine network parameters. The research results suggest that the capability of the UAV cruising at a one-kilometer and six-kilometer altitude plays a vital role in the transmission and redistribution of information and channel availability.

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LIST OF ACRONYMS AND ABBREVIATIONS

BER	bit error ratio
BPSK	binary phase-shift keying
C2	command and control
CBR	constant bit rate
COTS	commercial off-the-shelf
CSMA	carrier-sense multiple access
DOD	Department of Defense
DYMO	dynamic MANET on-demand
EM	electromagnetic
FSK	frequency-shift keying
FSO	free-space optics
FOV	field-of-view
GCS	ground control station
GEO	geosynchronous orbit
GFSK	Gaussian frequency-shift keying
GPS	Global Positioning System
ID	Identity
IEEE	Institute of Electrical and Electronics Engineers
LEO	low Earth orbit
LTE	long-term evolution
LOS	line-of-sight
MAC	medium access control
MEO	medium Earth orbit
QPSK	quadrature phase-shift keying
RF	radio frequency
SISO	single-input, single-output
SNR	signal-to-noise ratio
TDMA	time-division multiple access
UAS	unmanned aircraft system
UAV	unmanned aerial vehicle
UHF	ultra-high frequency
Wi-Fi	wireless fidelity
WLAN	wireless local area network

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I. INTRODUCTION

A study of cross-domain connectivity networks among two or more communication nodes in an operational scenario is analyzed in this chapter.

A. BACKGROUND

In communication networks, nodes can be referred to as communication starting points, redistribution relay points, or communication endpoints. Examples of nodes in an operational scenario include but are not limited to unmanned aerial vehicles (UAVs), a ground control station (GCS), and ground troops, as shown in Figure 1.

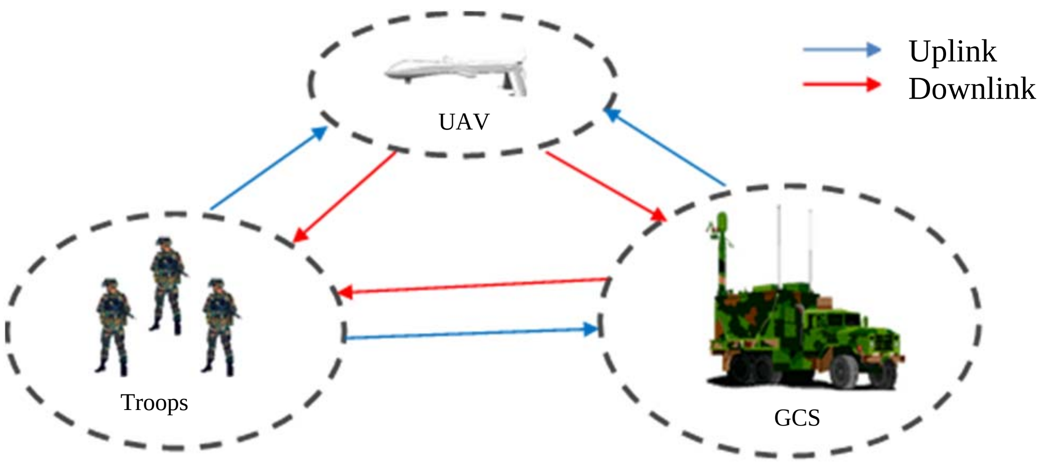

Figure 1. An Example of an Operational Scenario. Adapted from [1].

The emphasis of this thesis is on the air-to-ground, air-to-air, and air-to-space communication architecture in a cross-domain network.

B. PREVIOUS WORK

Yanar Burak [2] conducted detailed research using EXata (version 5.3) and suggested that the best configuration is to use two UAVs with dynamic MANET on-demand (DYMO) routing and IEEE 802.11b MAC protocols flying at an altitude of one kilometer in a double lawnmower mobility pattern. In [2] he noted that this configuration keeps the network congestion to a minimum. Burak also concluded that the current constraint for commercial off-the-shelf (COTS) transceivers is the slow data rate between the CubeSat and UAV; hence, a COTS transceiver with a higher data rate is needed to improve data transfer.

Drone swarms released from fighter jets has successfully performed a series of flying formation that mimic a surveillance mission [3]. In [3], 103 Perdix drones were deployed from three F/A-18 Super Hornets fighter jets working collectively. The drone swarm had the capability of making its own decisions and replicated a swarm in nature. A proof-of-concept using UAVs connected in a distributed network flying at different altitude is needed to determine the redistribution of information.

The concept of using a satellite to relay command and data to and from a UAV provides near-real-time data transfer between a UAV and a controller beyond line-of-sight [4]. In [4], a data rate of 30 Mbps was possible by using phased array or a gimballed dish antenna installed on the wings or fuselage of the UAV.

C. OBJECTIVES

The sole purpose of this research is to satisfy the connectivity requirements in an operational scenario to enable the exchange of information among two or more nodes across the communication channels that separate them. An illustration of the network connectivity between air, ground, sea, and space communication nodes is shown in Figure 2.

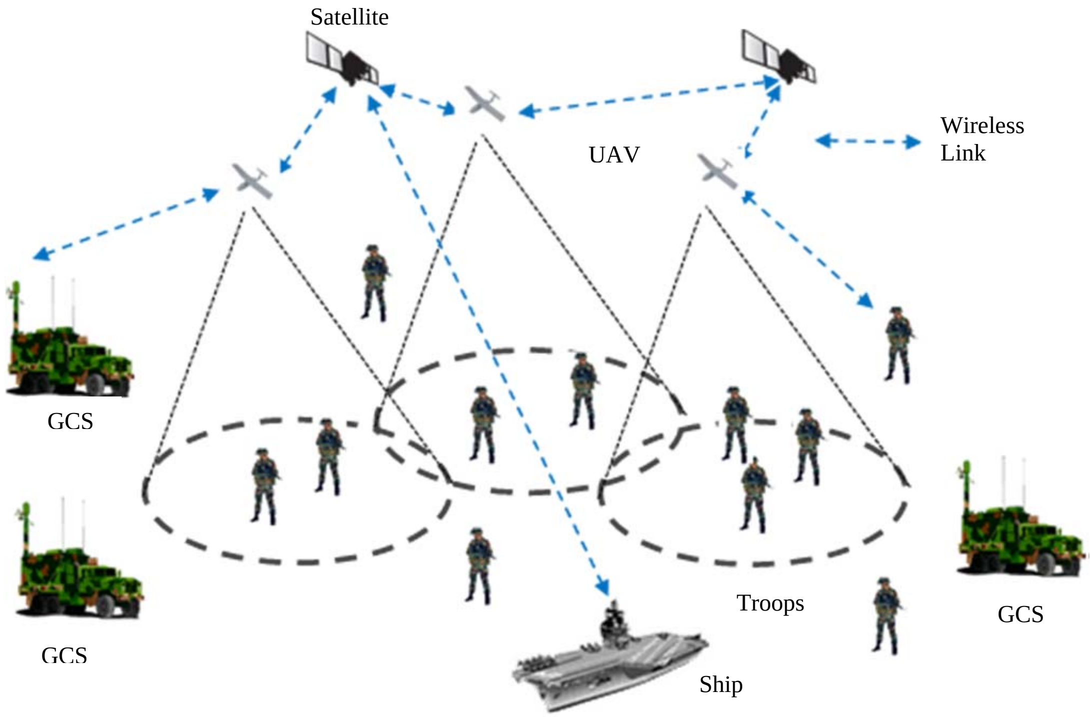

Figure 2. Network Connectivity Between Air, Ground, Sea, and Space Communication Nodes. Adapted from [1].

The objective of this research is to answer the following research questions:

- What are the communication networks available for two or more communication nodes?
- What are the communication architectures for ground-to-air and air-to-air networks?
- What are the concepts of operation necessary to support the communication architecture?
- What is the performance for the proposed multi-tier network architecture?
- What is the redundancy in the event of node or cluster failure?

D. CONTRIBUTIONS

This is a data gathering effort to consolidate the definition of communication nodes and identify them in a multi-tier network architecture. The operation of these nodes is discussed. As most communication nodes are designed as an integrated module or sub-system, the product specification of one component within a module or sub-system is not quantified; hence, assumptions must be made for that particular component for a link budget calculation. These assumptions can take reference from commonly used components or products that had been used for discussion in previous work.

The results of multiple simulations performed using the EXata (version 5.3) commercial networking software tool by Scalable Network Technologies to determine network parameters like delay, jitter, throughput, and link loss for signaling and data transfer among communication nodes in the multi-tier wireless-network communication architecture are also reported. The multi-tier wireless-communication network replicates the actual operational scenarios on the battlefield encountered by the military.

MATLAB was used as a tool for the graphical representation of data gathered from the calculation, simulation, and interpretation of results.

The outcome of the research provides a methodology for the communication network to connect a minimum of two communication nodes across a communication channel that separates them in an operational scenario.

E. THESIS ORGANIZATION

The communication approach for the multi-tier network architecture is provided in Chapter II of this thesis. The multi-tier wireless network architecture is visualized in Chapter III. The performance evaluation with the link analysis and simulation results is presented in Chapter IV. The operational scenarios are discussed in Chapter V. The findings and recommendations for future work are summarized in Chapter VI.

II. THE UAV AND CUBESAT

In this section, the communication approach using UAVs and CubeSats as communication nodes in the multi-tier network architecture is discussed.

A. UNMANNED AERIAL VEHICLES AND UNMANNED AIRCRAFT SYSTEMS

A UAV is an unmanned aircraft that is controlled with a direct data link by a GCS from takeoff until it leaves line-of-sight (LOS). The GCS then switches to a satellite link to maintain its control of the UAV, as depicted in Figure 3. The UAV utilizes the Global Positioning System (GPS) to determine its position, which is relayed to the GCS periodically [5]. The UAV is pre-programmed to fly continuously in circles to re-establish the data link in the event that it loses communication with the GCS. If the UAV experiences a permanent link loss or the number of reconnection attempts is exceeded, it returns to its base.

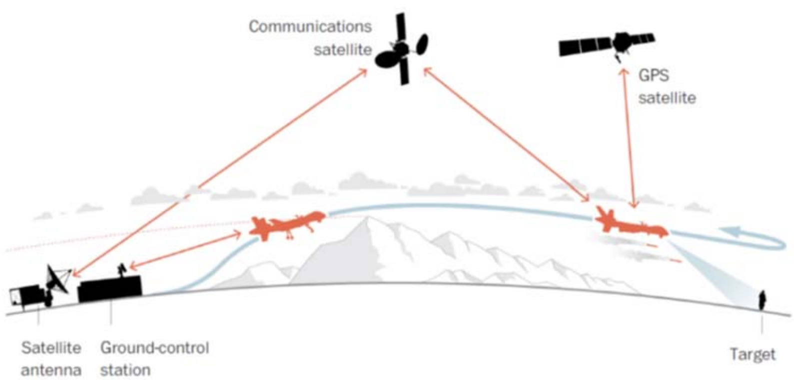

Figure 3. UAV Control. Source: [5].

A UAV performs the role of an “eye in the sky” by flying over a target-of-interest and using its onboard payload to capture visual imagery from above. The imagery can be in the form of photo snapshots, video streaming, a thermal signature, or a radiated emission plot capturing the view above the target-of-interest. For air-to-air and air-to-ground communications, the data collected from a distributed cluster of communication nodes can be forwarded using an air node like a UAV as a relay to retransmit back to command and control (C2), GCS, or an intermediate node, as depicted in Figure 4 [6].

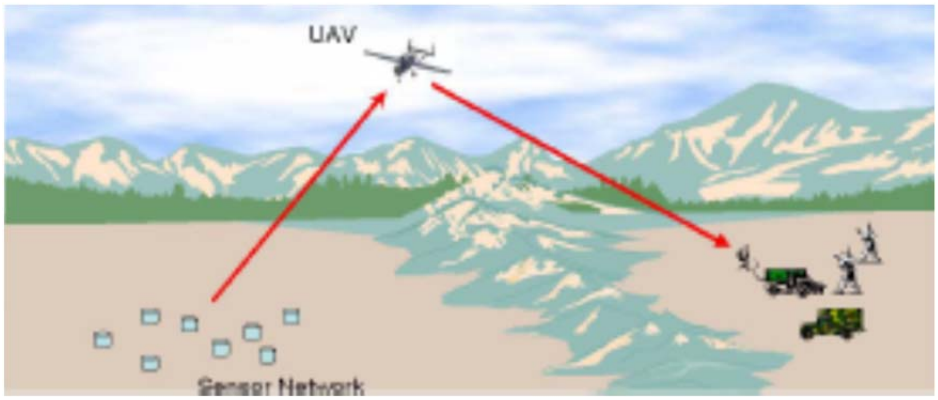

Figure 4. The UAV as a Relay. Source: [6].

One way to increase the operating range of a UAV without using a satellite link is to use mesh topology for the air-to-air communication whereby the data transmitted from one UAV to another is used to acknowledge commands from the controlling UAV, publish UAV flight plans, acquire the state of the aircraft, and send a control option and identification number, as illustrated in Figure 5 [7], [8].

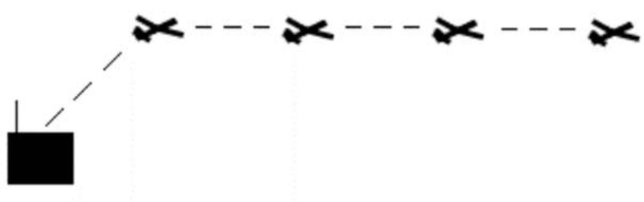

Figure 5. Mesh Network Topology between GCS and UAV. Source: [8].

In general, when there is a clustering algorithm for the randomly distributed ground nodes, a cluster head is elected in the network as the only node that interacts with the UAV to reduce overhead and promote energy efficiency. The air nodes transmit a known reference signal or data packet to the ground nodes or cluster head to initiate data transfer

[9]. An example of such a data packet, which consists of a wake-up, sensor-head, and slot allocation, is shown in Figure 6.

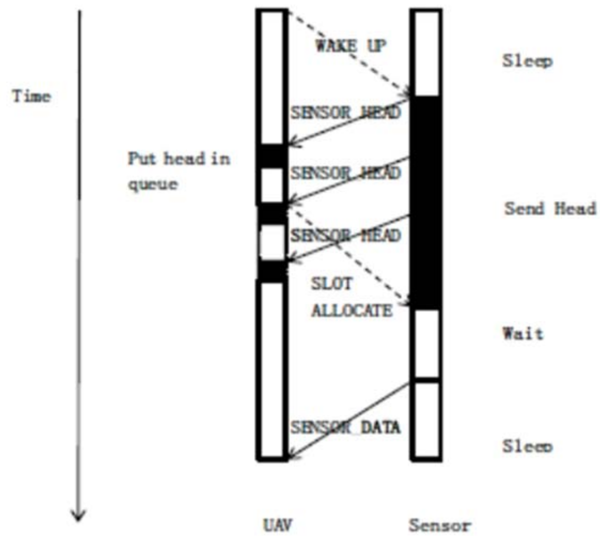

Figure 6. Data Packet Exchange between UAV and Sensor. Source: [9].

One way to maximize the coverage with the maximum number of nodes in less time is to use a UAV to sweep the area of operation in a pre-programmed mobility pattern. The circular, square, angular, and tractor mobility patterns are shown in Figure 7.

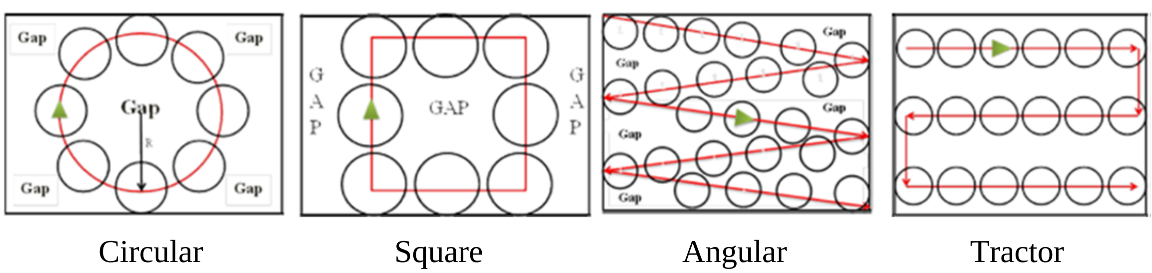

Figure 7. UAV Mobility Patterns. Adapted from [10].

The tractor mobility pattern is also known as the lawnmower mobility pattern. The double lawnmower mobility pattern uses two UAVs to fly in a crisscross manner wherein each uses the lawnmower mobility pattern to cover the area of operation [2].

There is no single or best mobility pattern that suits all scenarios. It differs on a case by case basis depending on the situation. For example, the angular mobility pattern provides the maximum node coverage, while the circular mobility pattern uses the minimum time per node as compared to the other mobility patterns [10].

A UAV is a component of an unmanned aircraft system (UAS). A UAS comprises the UAV, payload, human element, control element, weapon systems platform, display, communication architecture, life cycle logistics, and the operators or soldiers who support the UAS [11]. It can be described as a system of systems where a complex system with new functionality and performance is enabled by grouping dedicated and task-oriented systems together for the purpose of resources and capabilities consolidation [12]. Moreover, the U.S. Department of Defense (DOD) categorizes a UAS based on the maximum gross takeoff weight, nominal operating altitude, and airspeed as shown in Table 1 [11], [13].

Table 1. UAS Categories. Adapted from [11].

UAS Group	Max Gross Takeoff Weight (kg)	Nominal Operating Altitude (m)	Airspeed (km/h)	Current UAS in Operation
Group 1	0—9.07	< 365.76 above ground level (AGL)	185.2	RQ-11 Raven
Group 2	9.52—24.95	< 1066.8 AGL	< 463	ScanEagle
Group 3	< 598.74	< 5486.4 mean sea level (MSL)	< 463	RQ-7B Shadow, RQ-21 Blackjack
Group 4	> 598.74	> 5486.4 MSL	Any airspeed	MQ-8B Fire Scout, MQ-1A/B Predator, MQ-1C Gray Eagle
Group 5	> 1320	> 5486.4 MSL	Any airspeed	MQ-9 Reaper, RQ-4 Global Hawk, MQ-4C Triton

In summary, a UAS is a versatile complex system that can be customized to suit varying needs and tasks. For example, a UAV can be configured for either an operation or an endurance mode depending on the mission intent; it could be tasked with neutralizing threat in the shortest amount of time or performing reconnaissance or surveillance missions in an area of interest over a prolonged duration.

Since there are various types of UAVs being manufactured or assembled, we assume that the UAV antenna and transceiver used for link budget calculation are COTS products. In this thesis, we assume a Backfire 2.4 GHz Wi-Fi antenna and a single-input, single-output (SISO) DL2435-200 broadband radio transceiver, produced by Radio Labs, Inc. and Doodle Lab, respectively. The specifications of these products suggest that the operating range falls within the 2.4 GHz frequency band of IEEE 802.11 wireless local area network (WLAN) protocol. These products are shown in Figure 8.

Figure 8. Backfire 2.4 GHz Wi-Fi Antenna and SISO Broadband Transceiver. Source: Left, [14]; Right: [15].

The product specifications for the Wi-Fi antenna and DL2435-200 transceiver are summarized in Table 2.

Table 2. Wi-Fi Antenna and DL2435-200 Transceiver Specifications. Adapted from [14], [15].

Description	**Wi-Fi Antenna**	**DL-2435-200 Transceiver**
Frequency range	2400 to 2500 MHz	2335 to 2535 MHz
Receiver Sensitivity	-	-126 to -99 dBW
Modulation	-	BPSK, 16-QAM, 64-QAM
Gain	15 dBi	-
Beamwidth	32 degrees	-
RF Output	-	-16 to 0 dBW
Polarization	Vertical	-
Size	0.25 m diameter $\times$ 0.11 m depth	0.06 m length $\times$ 0.052 m width
Weight	0.91 kg	0.035 kg

UAV design faces ongoing challenges such as the compromise between minimizing takeoff weight and maximizing flight duration. For cases in which increased flight duration is desired, larger fuel tanks or battery cells substantially increase the overall takeoff weight of the UAV, and the paradox arises of whether to minimize weight or maximize flight time as the number one priority.

A technological trend for UAVs is moving toward alternative green energy, which includes fuel cells, bio-fuel, and solar cells, to overcome the limitation of flight time without significantly increasing weight of the UAV. Solar technology is considered a clean and limitless energy source [7]. Aircraft manufacturers and research centers like Boeing and ETH Zurich have begun developing smart solar-powered UAVs [16], [17]. Their aerospace companies and research centers strive toward lightweight and long-endurance flights without the need for carrying additional fuel onboard.

In addition, Internet companies like Google and Facebook have acquired solar-powered drone technology in an attempt to deliver the Internet to everyone whether in cities or remote areas of developing countries [18], [19], [20].

The benefits of using UAVs include their versatility and modular design. The UAV also has the flexibility to ascend to avoid detection or descend to establish connectivity with the ground and air nodes. The proposed multi-tier wireless network architecture leverages the UAV's capabilities to ascend and descend depending on scenarios to provide higher altitude coverage and to serve as the relay for information exchanges between low altitude air nodes and space nodes.

B. CUBESAT

A satellite can be placed in low Earth orbit (LEO), medium Earth orbit (MEO), or geosynchronous orbit (GEO). An illustration of the LEO, MEO and GEO orbital planes and their altitudes above the Earth's atmosphere is shown in Figure 9.

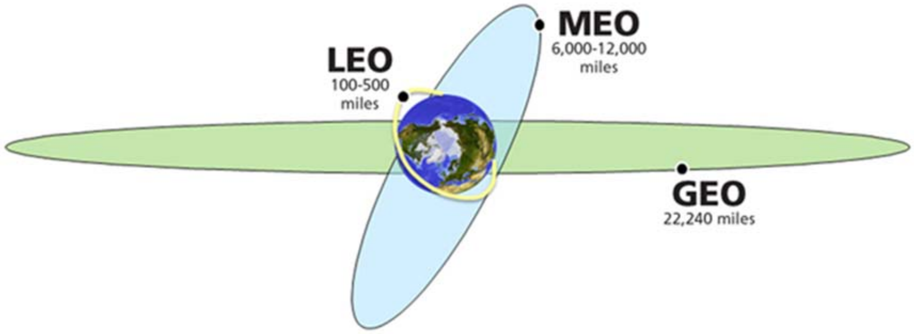

Figure 9. Orbital Planes. Source: [21].

A CubeSat is one type of miniaturized satellite residing in the LEO orbital plane. These satellites resemble a cube with relatively equal sides (e.g., 10.0 cm × 10.0 cm × 10.0 cm) and have a mass of not more than 1.33 kilograms per unit [22]. According to NASA, they are commonly deployed into low Earth orbit using NanoRacks CubeSat Deployers which can be launched from the International Space Station for the purpose of space research [23]. Examples of CubeSats are shown in Figure 10.

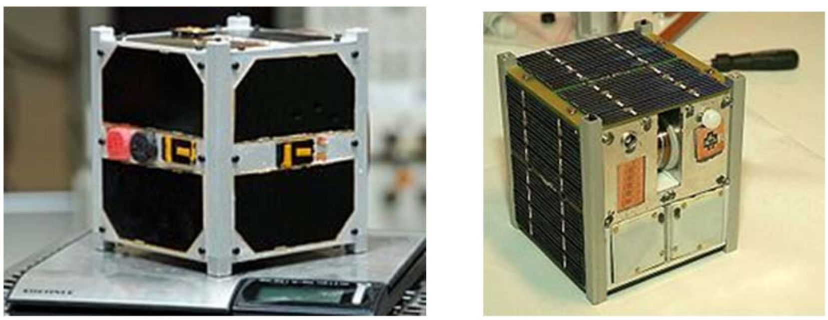

Figure 10. Examples of CubeSats (ESTCube-1 and nCUBE-2). Source: Left, [22]; Right, [24].

In general, satellites can be categorized based on their orbital plane. For miniaturized satellites like the CubeSat, there are several categories—minisatellite, mircosat, nanosat, picosat and femtosat—which usually depend on the total satellite mass including fuel [24]. A consolidation of different miniaturized satellite categories based on their mass is summarized in Table 3. A CubeSat falls under the category of either picosat or nanosat depending on its design.

Table 3. Miniaturized Satellite Categorization. Adapted from [24].

Satellite category	Mass (kg)	Satellite example
Minisatellite	100 to 500	Spirale
Microsat	10 to 100	Astrid-1
Nanosat	1 to 10	Exocube (CP-10)
Picosat	0.1 to 1	nCUBE-2
Femtosat	0.01 to 0.1	Sprite ChipSat

A CubeSat is a compact, lightweight, and low-cost solution for space exploration, communication relay, and scientific research. A CubeSat can be launched using a smaller, cheaper launch vehicle or by leveraging the thrust from larger launch vehicles to bring it to a desired orbit. The comparatively lower cost of CubeSat versus that of conventional satellite systems using COTS components and the ease of mass production of these satellites allows the creation of a communication network constellation to cover the entire globe [24].

CubeSat XI-V, also called Oscar 58, or CO-58, has been active and operational in LEO since it was launched on October 27, 2005 [25]. The specifications of CubeSat XI-V are summarized in Table 4. In addition, a real-time tracking of CubeSat XI-V's location captured on July 12, 2016 is shown in Figure 11 [25], [26].

Table 4. CubeSat XI-V Specifications. Adapted from [25].

Description	CubeSat XI-V (CO-58)
Designator	28895 / 05043F
Country of origin	Japan
Dimension	$10 \times 10 \times 10$ cm
Lowest altitude from Earth (perigee)	682 km
Highest altitude from Earth (apogee)	709 km
Telemetry	437.3450 MHz, FM FSK, 800.0 mW, half wave dipole
Downlink	437.4650 MHz, CW, 80.0 mW, half wave dipole
Mass	1 kg

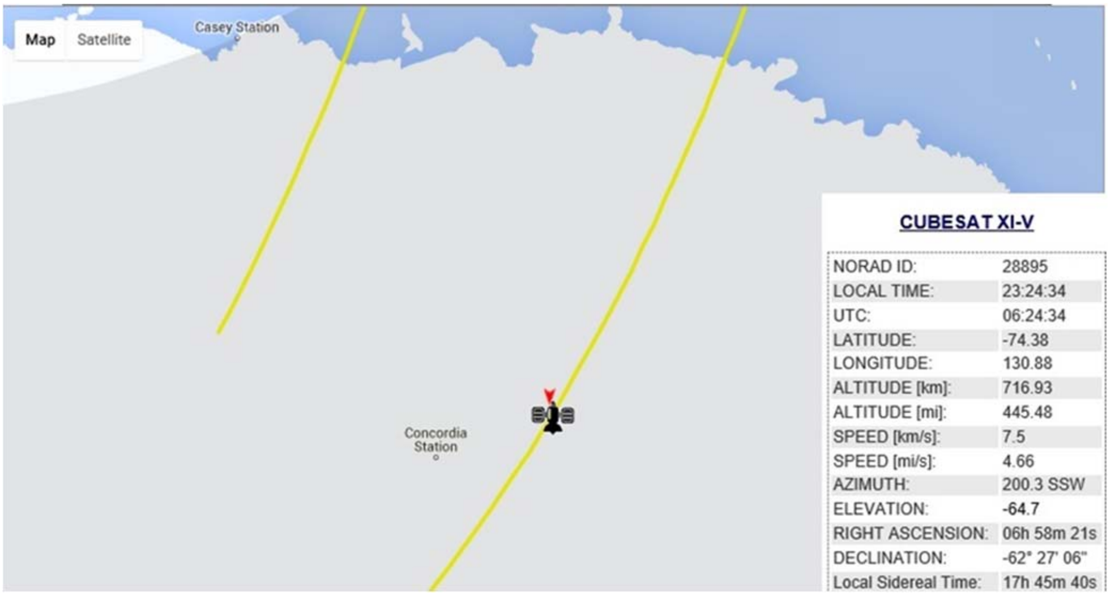

Figure 11. Real-time Tracking of CubeSat XI-V Captured. Adapted from [26].

For the purpose of discussion, we assume that the COTS products are used as the antenna and transceiver module for the CubeSat XI-V: the NanoCom ANT430 ultra-high frequency (UHF) turnstile antenna and the TRX-U UHF transceiver, produced by Gomspace and SpaceQuest, respectively. The components are shown in Figure 12.

Figure 12. NanoCom ANT430 Antenna and TRX-U UHF Transceiver.
Source: Left, [27]; Right, [28].

The product specifications suggest that the frequency range and the type of modulation matched the specifications of the CubeSat XI-V. An extract of the product specifications for the NanoCom ANT430 antenna and the TRX-U UHF transceiver are summarized in Table 5.

Table 5. NanoCom ANT430 Antenna and TRX-U UHF Transceiver Product Specifications. Adapted from [27], [28].

Description	**NanoCom AT430 Antenna**	**TRX-U UHF Transceiver**
Frequency range	400 to 550 MHz	370 to 470 MHz
Gain	1.6 dBi (maximum)	-
Beamwidth	Omni-directional	-
Polarization	Circular	-
Transmit data rate	-	2.4, 4.8, 9.6 and 19.2 Kbps
Receive data rate	-	2.4, 4.8, 9.6 and 19.2 Kbps
Modulation	-	FSK, GFSK
RF Output	-	1 to 6 W
Receiver Sensitivity	-	-150 dBW at 2400 bps, zero error -141 dBW at 19.2 Kbps, zero error
Size	$83 \times 57 \times 16$ mm	$83 \times 57 \times 16$ mm
Mass	140.0 g	140.0 g

The technology trend for miniaturized satellites, like the femtosatellite, is moving toward finding innovative solutions for propulsion, altitude control, communication, and computing systems to fit them all into the confined space within the CubeSat enclosure [22]. The comparably lower cost for launching CubeSats versus large satellites makes them attractive for space communications.

III. MULTI-TIER NETWORK ARCHITECTURE

The visualization of the proposed multi-tier network architecture; the node altitude, slant range, and footprint coverage for air nodes as well as frequency management plans, noise temperature, and noise figures are discussed in this chapter.

A. CONCEPT VISUALIZATION

The proposed multi-tier network architecture comprises several clusters of ground, air, sea and space nodes, as shown in Figure 13. These clusters may consist of ground troops who are deployed in the field, a pair of UAVs executing their roles of relaying and redistributing information, a constellation of LEO CubeSats, and a command ship as the end point communication node. The assignment of values to the communication links serves as an index for reference only.

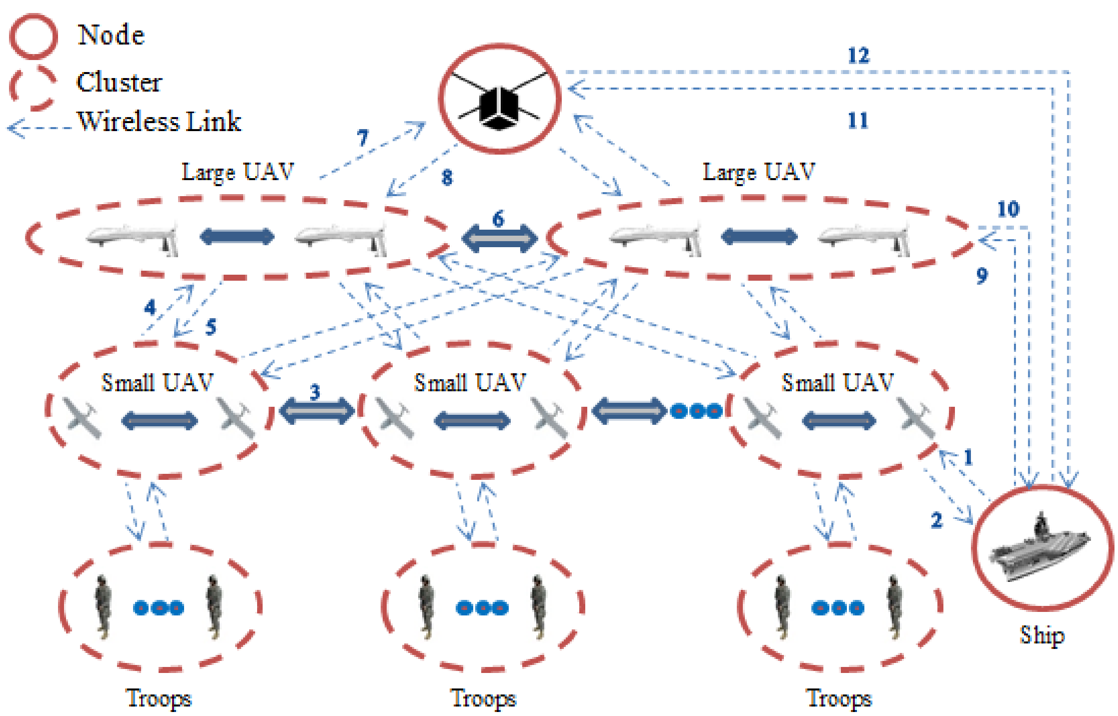

Figure 13. Multi-tier Network Architecture. Adapted from [1].

A cluster of ground troops is comprised of 15 distributed members connected in the same network. These ground-troop clusters are collectively known as *ground nodes* for easy reference.

Two low altitude UAVs cruising at a one-kilometer altitude in double lawnmower mobility patterns form a cluster to serve as an intermediate re-distribution relay point between high altitude UAVs and ground and sea nodes. These low altitudes UAV clusters are collectively known as *Air(S) nodes*, which represented *small* UAV air nodes, for easy reference.

Two high altitude UAVs cruising at a six-kilometer altitude in double lawnmower mobility patterns form a clustered pair to serve as an intermediate redistribution relay point between low altitude UAVs and CubeSats. These high altitude UAV clusters are collectively known as *Air(L) nodes*, which represent *large* UAV air nodes, for easy reference.

A CubeSat is a member of the constellation residing in the LEO plane at 300.0 km above the Earth's surface. The CubeSat is known as the *space node* for easy reference.

The ship is the command center and end point and is in charge of the flight path for the UAVs and information gathering. The ship is known as the *sea node* for easy reference.

B. NODE ALTITUDE

For the purpose of link budget analysis, the altitude difference between the cross-domain communication nodes is based on a flat-earth model whereby the relative altitude between each node is measured with reference to the Earth's surface. This altitude is used as a range calculation in the link budget analysis.

A satellite orbits at a high altitude in a large circle above the Earth's surface. The curvature of the Earth surface obscures the lower part of the target-of-interest when viewed across the horizon. The flat-earth model assumes an infinite surface stretching in two horizontal dimensions without obscuring the target-of-interest situated across the horizon. A flat-earth model is used to simplify the calculation of satellite and UAV altitude by having a common surface as reference without taking into consideration the curvature and uneven Earth's surface.

The ground, Air(S), Air(L), as well as space and sea nodes are assumed to reside at altitudes of 0.0 m, 1.0 km, 6.0 km, 300.0 km, and 0.0 m, respectively, as illustrated in Figure 14.

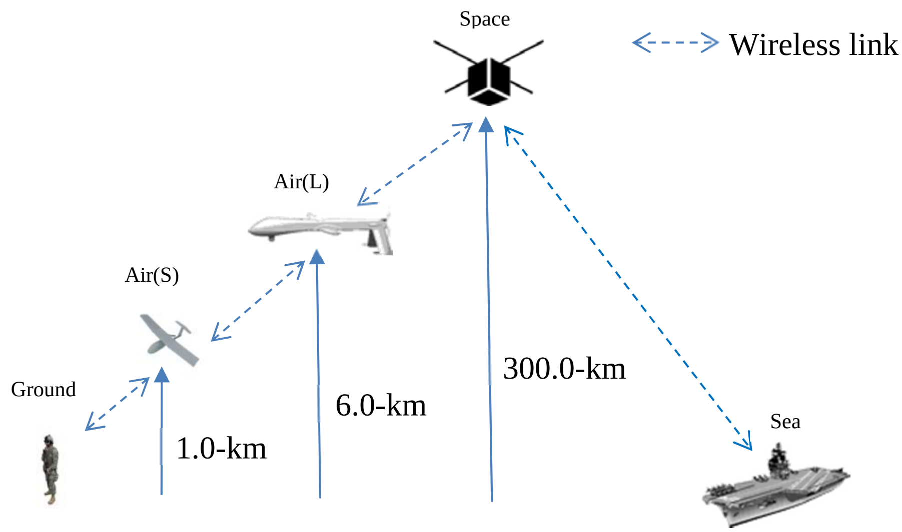

Figure 14. Altitudes for Cross-Domain Nodes Using the Flat-Earth Model. Adapted from [1].

C. SLANT RANGE

The slant range is a LOS distance from a measurement point (node) to the location of the target node. Based on the geometry of a triangle, the slant range is always greater than the geographical distance and height of the target node's location. For the case of a moving air node, the corresponding range is constantly updated due to varying geographical distances and altitudes among the nodes over the time of measurement.

The slant range is a common entity used in range-finding electronic equipment and network simulation software like EXata to determine the LOS distance between two nodes. This LOS distance calculation measures the distance to target in a straight line of path.

For a satellite at an altitude h above the Earth's surface and traversing in LEO, the slant range R_{LEO} between the Earth station and satellite is given by [29]

$$R_{LEO} = R_z\left[\sqrt{\left(\frac{R_z+h}{R_z}\right)^2 - \cos^2(\mathrm{E})} - \sin(E)\right], \tag{1}$$

where R_z is the Earth radius, 6,371.0 km, h is the altitude of the LEO satellite above the Earth's surface, 300.0 km, and E is the elevation angle (degrees).

Alternatively, the elevation angle E can be represented in terms of slant range using [29]

$$\sin\left(E\right) = \frac{h\left(h+2R_z\right) - R_{LEO}{}^2}{2R_{LEO}R_z}. \tag{2}$$

For illustration purposes, we determine the slant range R_{LEO} by considering a range of E values. The calculated slant range R_{LEO} is tabulated in Table 6.

Table 6. Slant Range of LEO Satellites for a Given Elevation Angle

Elevation Angle E (degrees)	**Slant Range R_{LEO} (km)**
10	1160.08
20	763.89
30	564.17
40	452.69
50	385.61
60	343.85
70	318.31
80	304.42
90	300.00

D. FOOTPRINT COVERAGE FOR AIR NODES

The projection of the aerial coverage is dependent on the field-of-view (FOV) and cruising altitude of the air node. The footprint area coverage is illustrated in Figure 15.

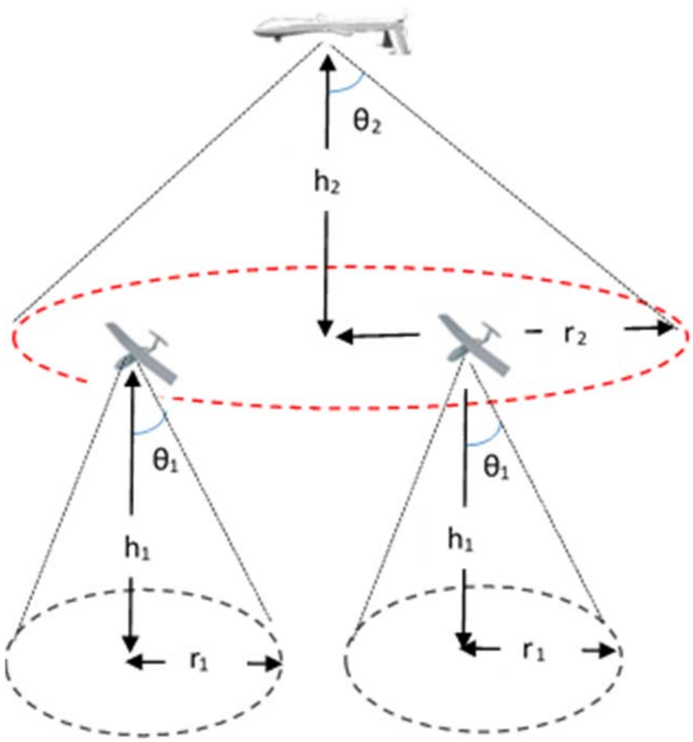

Figure 15. Footprint for Surveilling Air Nodes. Adapted from [1].

A flat earth model is assumed for the Earth's surface, and a constant altitude is assumed for the air node. The parameter r_i (for $i = 1, 2$) denotes the radius of the circular footprints, which can be calculated from

$$r_i = h_i \tan\theta_i \ , \tag{3}$$

where h_1 is the altitude of Air(S) node, 1.0 km, h_2 is the altitude of Air(L) node, 6.0 km, θ_1 is the half-FOV angle measured at the surveilling Air(S) node (degree), and θ_2 is the half-FOV angle measured at the surveilling Air(L) node (degree).

The footprint coverage $A_{coverage}$ is the area of a circle can be calculated from

$$A_{coverage} = \pi r_i^2 \ , \tag{4}$$

and is proportional to the radius r_i.

The area of operation is confined within an enclosed area of 1,500.0 m by 1,500.0 m where the information exchange between ground and air nodes is required. The multi-tier architecture requires the Air(L) node to transmit or redistribute the information to another node with minimum delay to mitigate a situation commonly known as network bottleneck. A network bottleneck occurs when the information at a particular node waits in queue for transmission, but the recipient nodes are unavailable. This network congestion eventually affects the link throughput since the data packets take longer to transmit over the channel.

For the Air(S) node, the approach to provide coverage for an enclosed area is to use a circular footprint of a 100.0-m radius and a double lawnmower mobility pattern.

The double lawnmower mobility pattern for the Air(S) node is based on recommendations from [2]. This approach is illustrated in Figure 16.

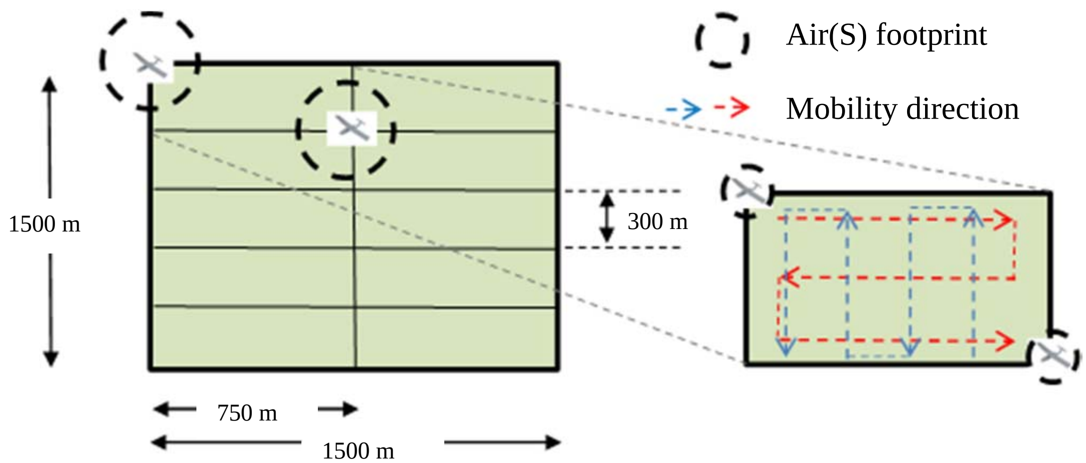

Figure 16. Cascading Air(S) Footprint—Top View. Adapted from [1].

For the Air(L) node, the approach to provide coverage for an enclosed area is to use a circular footprint of a 200.0-m radius and a double lawnmower mobility pattern.

The double lawnmower mobility pattern is also used for Air(L) node based on recommendations from the previous work [2]. This is illustrated in Figure 17.

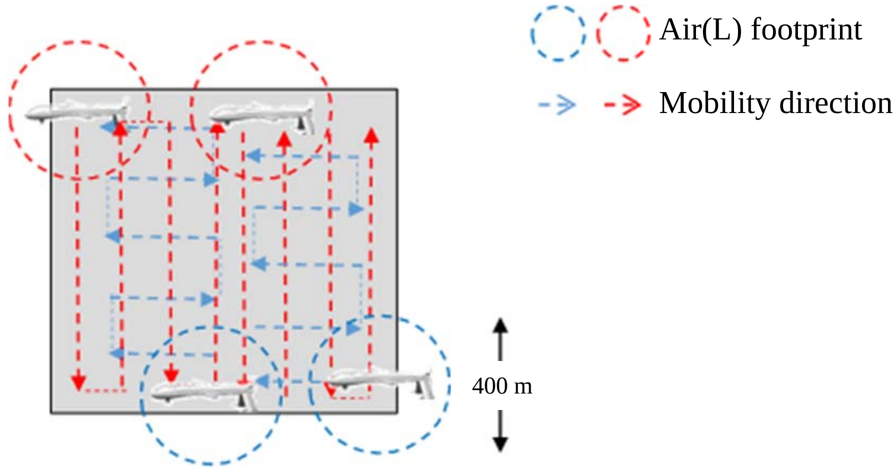

Figure 17. Cascading Air(L) Footprint—Top View. Adapted from [1].

E. FREQUENCY MANAGEMENT PLAN

Frequency management for the operational scenario is one of the most critical system design considerations. It is needed to minimize the likelihood of adjacent channel interference in the electromagnetic (EM) spectrum. Frequency management plans do not guarantee zero interference in the actual implementation but greatly reduce the adjacent channel interference in conjunction with adequate mitigating measures.

Apart from specifying the center frequency for each channel, the Institute of Electrical and Electronics Engineers (IEEE) 802.11 also specifies an envelope for maximum power distribution in the channel. The envelope requires the signal to be attenuated by a minimum of 20.0 dB from peak amplitude at ± 11.0 MHz from the center frequency [30].

For the purpose of simulation, the IEEE 802.11b standard was chosen as the medium access control (MAC) protocol. It uses the 2.4 to 2.5-GHz frequency band for channel allocation. In addition, the IEEE 802.11b standard sub-divides the frequency band into 14 channels, which are spaced 5.0 MHz apart, beginning with channel 1 centered at 2.412 GHz as shown in Figure 18. Out of the 14 sub-divided channels, there are only four non-overlapping channels that can be used collectively without crossing into adjacent channels [30].

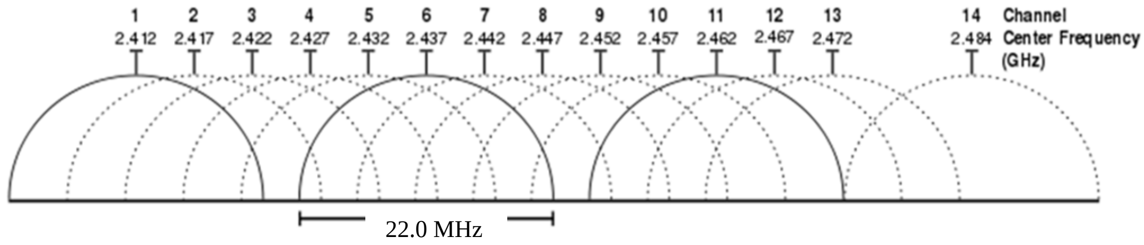

Figure 18. IEEE 802.11 Channel and Frequency Allocation. Adapted from [30].

Due to a limited number of non-overlapping channels, the channel bandwidth becomes a scarce resource for a multiple access network like the proposed multi-tier network. One method for overcoming this limitation is to employ time-division multiple access (TDMA), which shares the same frequency channel with multiple users by allocating a different time slots to each user and transmitting in quick succession [31].

An alternative method is to employ software blanking to allow only the source to use the channel and disallow all other users from accessing any other channels for transmission. Other techniques for software blanking include filtering or eliminating transmissions from adjacent channels, so the signal originating from the source is not affected by the adjacent channel interference. In general, the software-blanking method requires sophisticated software algorithms and digital signal processing for effective implementation on the intended channel.

The proposed frequency management plan for the multi-tier network is tabulated in Table 7. Furthermore, the multi-tier network architecture uses different channel frequency to form a cluster consisting of node members that are identified to be in a common group. The node members within the same cluster are able to exchange and share information through the allocated channel frequency.

Table 7. Frequency Management Plan. Adapted from [30].

Link	Type of link	IEEE 802.11 Channel Number	Frequency Band (MHz)	Center Frequency (MHz)
Ground-Air(S)	Signal/Data	11	2451—2473	2462
Air(S)-Ship	Signal/Data	1	2401—2423	2412
Air(S)-Air(S)	Signal/Data	6	2426—2448	2437
Air(S)-Air(L)	Signal/Data	4	2416—2438	2427
Air(L)-Air(S)	Signal/Data	9	2441—2463	2452
Air(L)-Air(L)	Signal/Data	7	2431—2453	2442
Air(L)-Space	Signal/Data	Not Applicable	370—470	440
Space-Air(L)	Signal/Data	Not Applicable	370—470	445
Ship-Air(L)	Signal/Data	13	2461—2483	2472
Air(L)-Ship	Signal/Data	8	2436—2458	2447
Ship-Space	Signal/Data	Not Applicable	370—470	435
Space-Ship	Signal/Data	Not Applicable	370—470	430

In order to differentiate one cluster from the other, the nodes are grouped in a separate cluster manner such that each cluster is defined by an allocated frequency in the simulation model as shown in Figure 19.

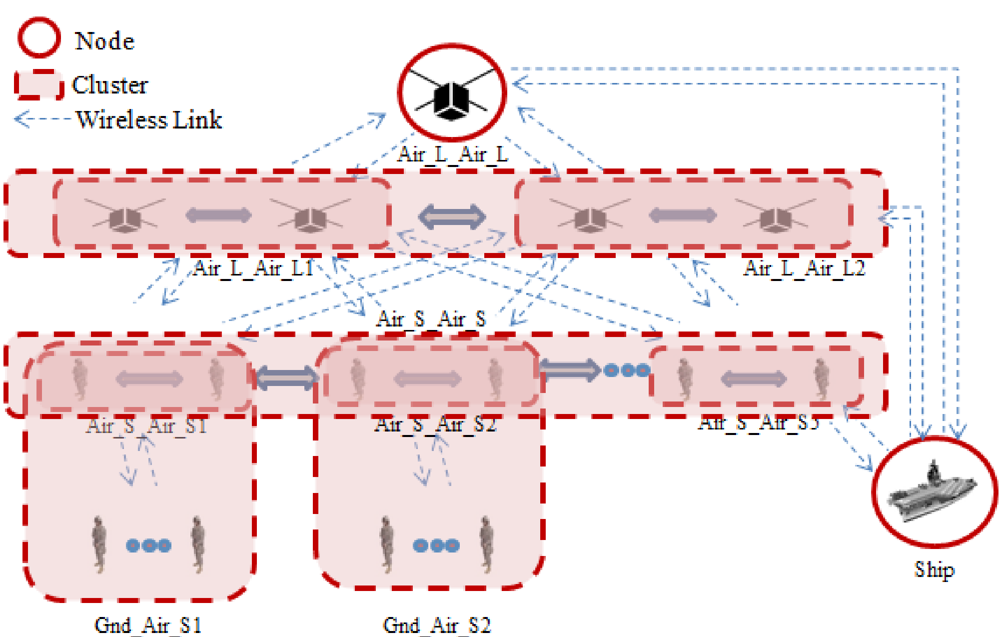

Figure 19. Nodes Grouping. Adapted from [1].

The detailed grouping of the nodes into clusters is shown in Table 8.

Table 8. Nodes Clustering

Nodes ID	Link	Cluster ID	Frequency Allocated (MHz)
7, 8, 17 through 31	Ground-Air(S)	Gnd_Air_S1	2462.10
9, 10, 32 through 46	Ground-Air(S)	Gnd_Air_S2	2462.20
7 through 16	Air(S)-Air(S)	Air_S_Air_S	2437.00
7, 8	Air(S)-Air(S)	Air_S_Air_S1	2437.10
9, 10	Air(S)-Air(S)	Air_S_Air_S2	2437.20
11, 12	Air(S)-Air(S)	Air_S_Air_S3	2437.30
13, 14	Air(S)-Air(S)	Air_S_Air_S4	2437.40
15, 16	Air(S)-Air(S)	Air_S_Air_S5	2437.50
2 through 5	Air(L)-Air(L)	Air_L_Air_L	2442.00
2, 3	Air(L)-Air(L)	Air_L_Air_L1	2442.10
4, 5	Air(L)-Air(L)	Air_L_Air_L2	2442.20

F. NOISE TEMPERATURE AND NOISE FIGURE

The noise temperature is not the physical temperature quantity of a component but a method to express and quantify the available noise power introduced by components or sources into the system block. The system noise temperature T_{sys} can be determined using

$$T_{sys} = T_{in} + T_e \ , \tag{5}$$

where T_{in} is the input noise temperature, and T_e is the effective noise temperature generated by all sources in the system block.

One application of the noise temperature is to define the system's noise factor F in terms of the effective noise T_e and standardized constant temperature T_o using

$$F = 1 + \frac{T_e}{T_o} \ , \tag{6}$$

where T_o is the standardized constant temperature, 290 K.

The corresponding system's noise figure NF, which is the decibel representation of the noise factor F, can be determined using

$$NF = 10\log(F) \ . \tag{7}$$

The noise factor F for cascading blocks is determined from

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_n - 1}{G_1 G_2 ... G_{n-1}} \ , \tag{8}$$

where F_1 is the noise factor for first block, F_2 is the noise factor for second block, G_1 is the gain for first block, F_3 is the noise factor for third block, G_2 is the gain for the second block, F_n is the noise factor for n^{th} block, and G_{n-1} is the gain for $(n-1)^{th}$ block [32].

The corresponding NF for cascading blocks can be determined using

$$NF = 10\log\left(F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + ... + \frac{F_n - 1}{G_1 G_2 ... G_{n-1}} \right) \ . \tag{9}$$

The block diagram of an antenna with cascading blocks at the receiver is illustrated in Figure 20.

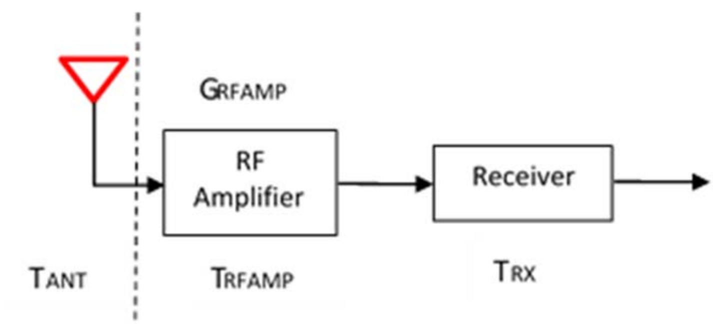

Figure 20. Block Diagram of Antenna with Cascading Blocks

The equivalent system noise temperature T_{sys} when an antenna is added to the cascading blocks at the receiver is determined using

$$T_{sys} = T_{ANT} + T_{RFAMP} + \frac{T_{RX}}{G_{RFAMP}} \ , \tag{10}$$

where T_{ANT} is the noise temperature of the antenna, T_{RFAMP} is the effective noise temperature of the radio frequency (RF) amplifier, T_{RX} is the effective noise temperature of the receiver, and G_{RFAMP} is the gain of the RF amplifier.

For purpose of illustration, we analyze the Predator UAV system [33] in order to have a better understanding on the typical values expected for the noise figure based on their specification. The overall noise factor for the Predator UAV receiver is calculated to be 1.52 using (8) where F_1 is the noise factor of the Predator UAV RF amplifier, 1.51 implies 1.8 dB, F_2 is the noise factor of the Predator UAV receiver block, 1.585 implies 2.0 dB, and G_1 is the gain of the Predator UAV RF amplifier, 63.10 implies 18.0 dB. The overall NF using (9) is calculated to be 1.818 dB.

For simplicity, all communication nodes have an overall F of 2.0 for the link budget calculation. The effective noise temperature of the receiver is calculated by re-arranging (6) such that $T_{RX} = T_e = (F-1)T_o =$ 290.0 K. The equivalent system noise temperature T_{sys} for the ground, Air(S), Air(L), and sea and space nodes is calculated to be 584.6 K using (10) where T_{ANT} is the noise temperature of the antenna, 290.0 K, T_{RFAMP} is the effective noise temperature of the RF amplifier, 290.0 K, and G_{RFAMP} is the gain of the RF amplifier, 63.10, which implies 18.0 dB. G_{RFAMP} is cross-referenced from the Predator UAV for the purpose of illustration.

An overview of the noise temperature for the multi-tier communication network is shown in Figure 21.

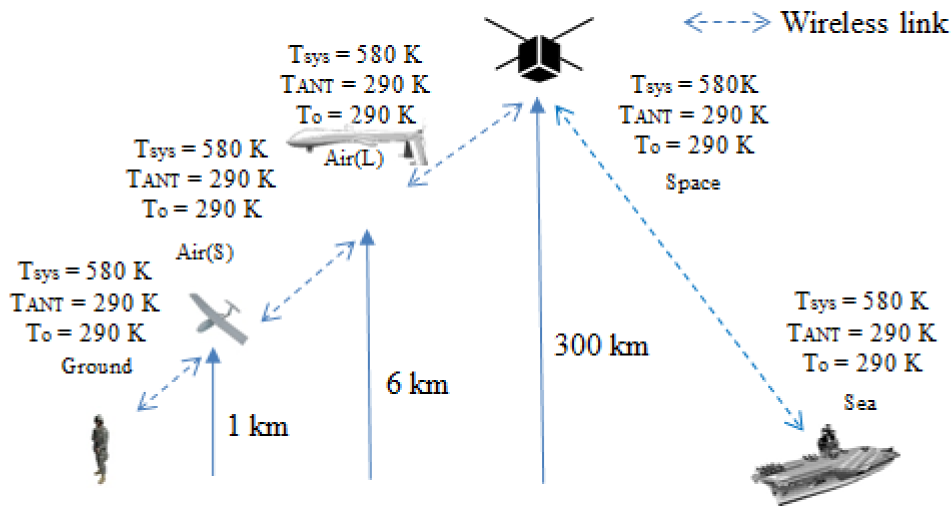

Figure 21. Noise Temperature for Cross-Domain Nodes. Adapted from [1].

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IV. PERFORMANCE EVALUATION

The calculation and simulation results using link budget analysis and the EXata software tool, respectively, are presented in this chapter.

A. CALCULATION USING LINK BUDGET ANALYSIS

The results from calculations using the Friss transmission formula to determine parameters like free-space path loss, received power and signal-to-noise ratio (SNR) based on the multi-tier communication network architecture shown in Figure 13 are consolidated in this section.

For the purpose of discussion, we consider one communication link from the multi-tier network and proceed through the derivations and assumptions that determine the link margin. A similar approach is applied to the remaining communication links. A visual representation of the communication link between a ground node and an Air(S) node is illustrated in Figure 22.

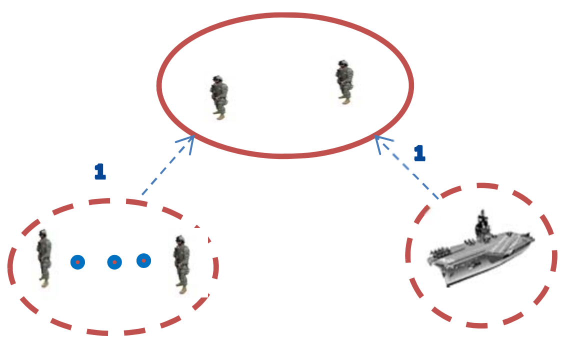

Figure 22. Ground-to-Air Signal Communication Link. Adapted from [1].

The free-space path loss L_R for the Ground-Air(S) link can be determined using

$$L_R = 10\log_{10}\left[\frac{4\pi R}{\lambda}\right]^2 , \tag{11}$$

where R is the range between two communication nodes, 1.0 km, $\lambda = c/f$ is the wavelength, 0.122 m, c is the speed of light, 3×10^8 m/s, and f is the operating frequency for the link, 2.4621×10^9 Hz. Based on the wavelength and range between the two communication nodes, the free-space path loss for the Ground-Air(S) link is calculated to be 100.3 dB.

The received power P_{RX} in dBW can be determined using

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX} \ , \tag{12}$$

where P_{TX} is the transmitted output power, 0.074 W implies –11.3 dBW, G_{TX} is the transmitter gain, 1.585 implies 2.0 dBi, L_{TX} is the transmitter loss from coaxial cables and connectors, 1.585 implies 2.0 dB, L_{FS} is the free-space path loss, 1.06×10^{10} implies 100.3 dB, L_M is the miscellaneous loss from fading, 10.0 dB, G_{RX} is the receiver gain, 1.585 implies 2.0 dBi, and L_{RX} are the receiver losses, 1.585 implies 2.0 dB. Based on the link parameters, the received power P_{RX} for the Ground-Air(S) link is calculated to be –121.5dBW.

The energy per bit E_b in dBW/Hz or dBJ can be determined from

$$E_b = P_{RX} - R \ , \tag{13}$$

where P_{RX} is the received power for the Ground-Air(S) link, –121.5dBW, and R is the bit rate, 11×10^6 bps implies 70.4 dBbps [34]. Based on the given bit rate, the energy per bit E_b for the Ground-Air(S) link is calculated to be –191.9 dBJ.

The noise spectral density N_o in dBW/Hz can be determined by

$$N_o = k + T_{sys} \ , \tag{14}$$

where k is the Boltzmann constant, 1.38×10^{-23} W/K-Hz, which implies –228.6 dBW/K-Hz, and T_{sys} is the system noise temperature = 584.6 K implies 27.7 dBK. The N_o for the Ground-Air(S) link is calculated to be –200.9 dBW/Hz.

The calculated energy per bit over noise spectral density or SNR per bit $E_b/N_o[calculated]$ can be determined using

$$\frac{E_b}{N_o}\left[calculated\right] = \frac{P_{RX}}{N_o R} \ , \qquad (15)$$

where P_{RX} is the received power for the Ground-Air(S) link, 7.08×10^{-13} implies –121.5dBW, N_o is the spectral noise density, 8.13×10^{-21} implies –200.9 dBW/Hz, and R is the bit rate, 11×10^{6} bps implies 70.4 dBbps [34]. The calculated SNR per bit for the Ground-Air(S) link is calculated to be 7.91, which implies 9.0 dB, using (15).

The link margin LM can be determined using

$$LM = \frac{E_b}{N_o}\left[calculated\right] - \frac{E_b}{N_o}\left[required\right] - LP + CG \ , \qquad (16)$$

where $E_b/N_o\left[required\right]$ is the required SNR per bit for quadrature phase-shift keying (QPSK) with a bit error ratio (BER) of 10^{-4}, 6.76 implies 8.3 dB, LP is the link provision, 2.0 implies 3.0 dB, and CG is the coding gain for QPSK, 2.512, implies 4.0 dB.

The link margin is calculated to be 1.7 dB using (16) for the uplink between a ground node and Air(S) node cruising at a one-kilometer altitude as shown in Table 9.

Table 9. Link Budget Analysis for Link #1—Ground-to-Air(S)

Link	**Ground-Air(S)**
Power Transmitted (dBW)	–11.3
Transmitter Cable Loss (dB)	2.0
Transmitter Antenna Gain (dBi)	2.0
Free-Space Path Loss (dB)	100.3
Miscellaneous Loss (dB)	10.0
Receiver Antenna Gain (dBi)	2.0
Receiver Cable Loss (dB)	2.0
Power Received (dBW)	–121.5
Bit Rate (dBbps)	70.4
Energy Per Bit (dBJ)	–191.9
Equivalent System Noise Temperature (dBK)	27.7
Noise Spectral Density (dBW/Hz)	–200.9
Calculated Eb/No (dB)	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5
Link Provision (dB)	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5

The power for the range of antenna gains follows a linear relationship, as shown in Figure 23. The 0-dB gain corresponds to an omni-directional antenna, which radiates equally in all directions. This observation aligns with the Friss equation since a channel with a lower gain requires higher transmission power.

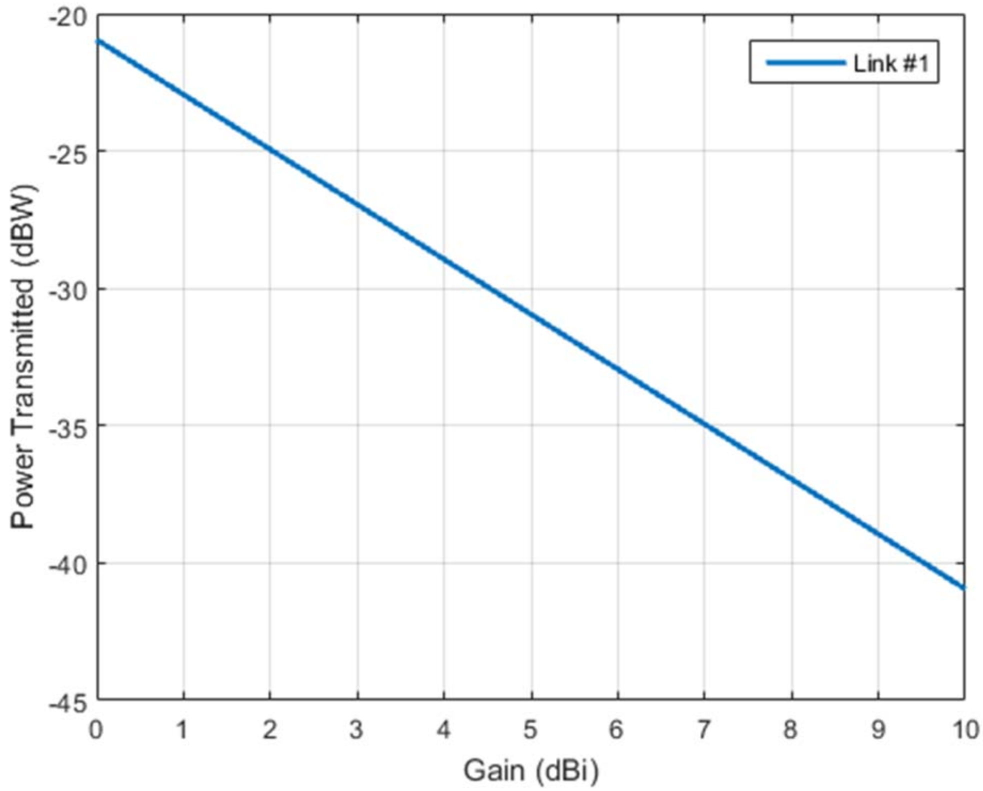

Figure 23. Relationship Between the Power Transmitted and Antenna Gain for Link #1

The transmitted power for a range of operating frequencies follows a curve, with increasing transmission power based on a pre-determined transmitted or received antenna gain, as shown in Figure 24. The results align with the Friss equation since a channel with increasing frequency has greater free-space path loss which, in turn, requires a higher transmission power at the source.

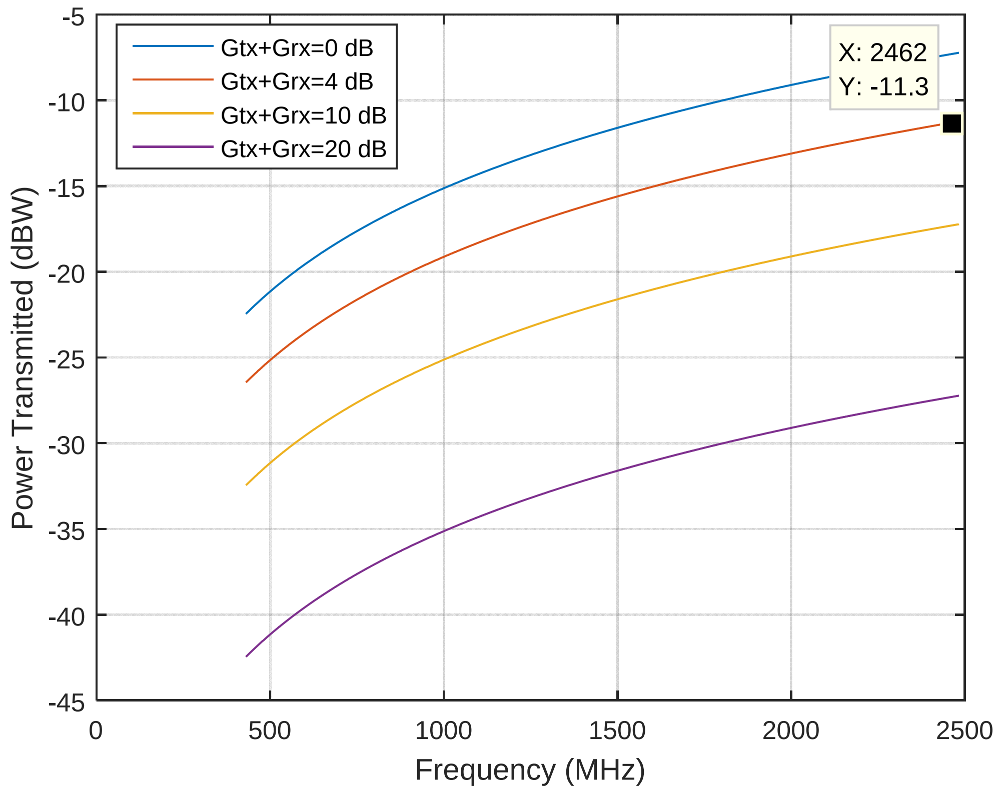

Figure 24. Relationship Between Power Transmitted and Operating Frequencies Against Pre-determined Antenna Gains for Link #1

In order for the surveillance air node to sufficiently encompass the enclosed area of 1,500.0 m by 1,500.0 m, the multi-tier network architecture specifies the separation distance between the Air(S) nodes and defines the mobility pattern for them.

The beamwidth for the Air(S) node is calculated to be 5.7 degrees after re-arranging (3), where r_1 is the radius of the circular footprint, 100.0 m, and h_1 is the altitude of Air(S) node, 1.0 km.

The beamwidth for the Air(S) node over a range of altitudes is shown in Figure 25.

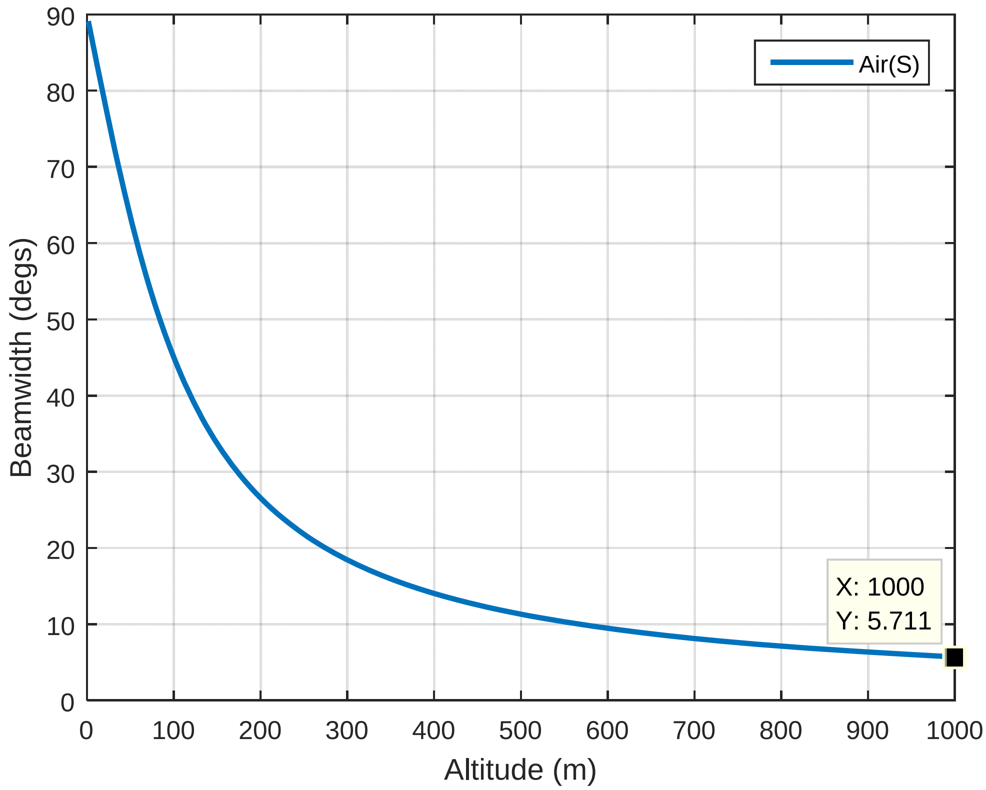

Figure 25. Beamwidth Versus Altitude for Air(S) Node

Similarly, for the Air(L) nodes, the beamwidth for the Air(L) node is calculated to be 2.3 degrees after re-arranging (3), where r_2 is the radius of the circular footprint, 200.0 m, and h_2 is the altitude difference between the Air(L) and Air(S) node, 5.0 km.

The beamwidth for the Air(L) node over a range of altitudes is shown in Figure 26.

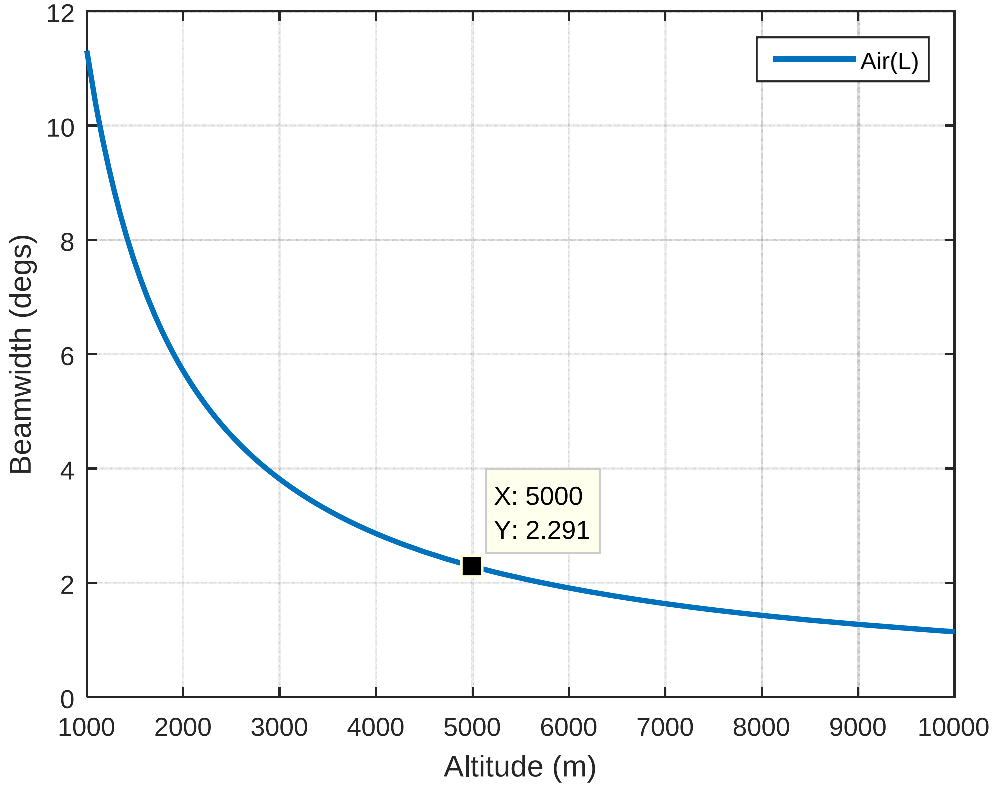

Figure 26. Beamwidth Versus Altitude for Air(L) Node

We see that the air node requires a smaller beamwidth at high altitudes to cover the same footprint area.

The overall link budget analysis containing all the connectivity links using a data rate of 11.0 Mbps for the multi-tier network architecture is consolidated in Tables 10 to 12.

Table 10. Link Budget Analysis for Links #1–4

Link	**1**	**2**	**3**	**4**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)
Power Transmitted (dBW)	–11.3	–11.4	–4.8	2.6
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0
Power Received (dBW)	–121.5	–121.5	–121.5	–121.5
Bit Rate (dBbps)	70.4	70.4	70.4	70.4
Energy Per Bit (dBJ)	–191.9	–191.9	–191.9	–191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5

Table 11. Link Budget Analysis for Links #5–8

Link	**5**	**6**	**7**	**8**
Signal	Air(L)-Air(S)	Air(L)-Air(L)	Air(L)-Space	Space-Air(L)
Power Transmitted (dBW)	2.7	–4.8	1.0	1.1
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	114.2	106.7	134.7	134.8
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0
Power Received (dBW)	–121.5	–121.5	–144.5	–144.5
Bit Rate (dBbps)	70.4	70.4	47.5	47.5
Energy Per Bit (dBJ)	–191.9	–191.9	–191.9	–191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5

Table 12. Link Budget Analysis for Links #9–12

Link	**9**	**10**	**11**	**12**
Signal	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	4.3	4.3	1.1	1.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0
Power Received (dBW)	–121.5	–121.5	–144.5	–144.5
Bit Rate (dBbps)	70.4	70.4	47.5	47.5
Energy Per Bit (dBJ)	–191.9	–191.9	–191.9	–191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5

Link budget analysis for data rates of 1.0, 2.0, 5.5, and 54.0 Mbps for the multi-tier network architecture are consolidated in Tables 15 to 22 of the Appendix A. Furthermore, the link budget analysis using the SNR per bit of 9.0, 12.0, 15.0, and 18.0 dB are consolidated in Tables 23 to 52 of the Appendix A.

B. SIMULATION USING EXata (VERSION 5.3)

The commercial software tool called EXata (version 5.3) from Scalable Network Technologies is introduced in this section. A brief introduction to the software and the parameters used for the simulation are presented; thereafter, the simulation model of the multi-tier network architecture for EXata and results from the simulation are presented.

1. EXata Software Interface

The EXata software has an interactive and easy-to-use interface where most of the common functions are available on the main screen once the program has launched. A snapshot of the EXata software interface is shown in Figure 27.

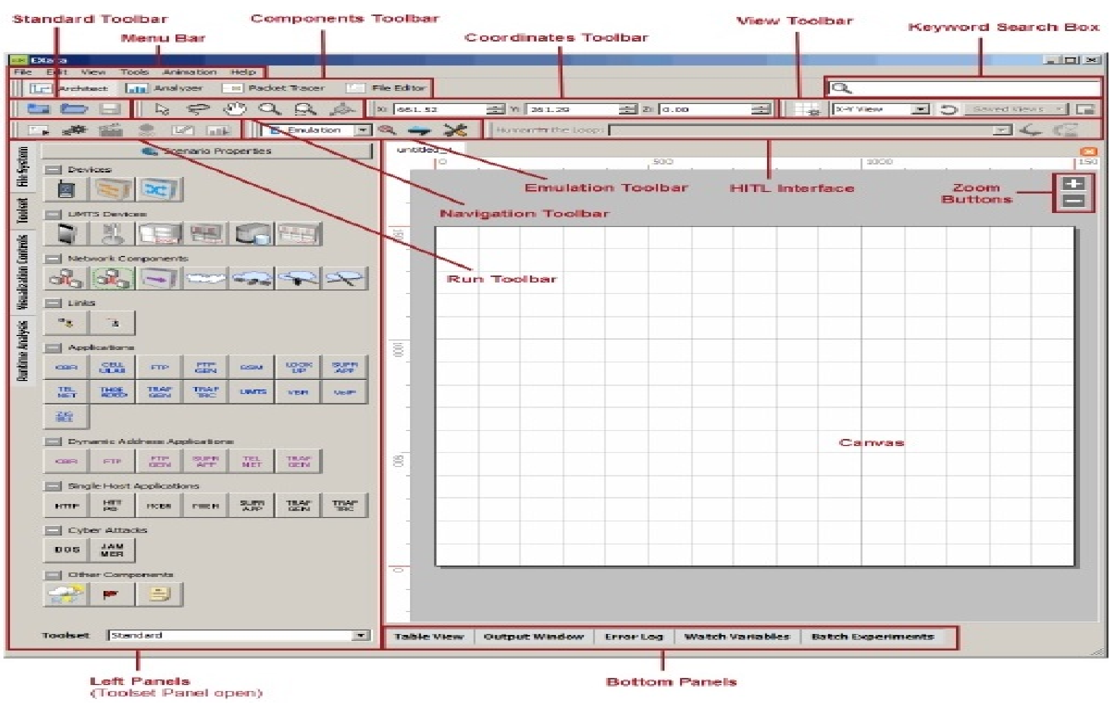

Figure 27. EXata Software Interface. Source: [34].

The EXata software has a user-friendly interface which allows users to click and drag network device nodes from the left toolset panel to setup the network architecture by placing these nodes on the canvas (white grid) and linking them to form the desired network. An illustration using EXata for a ground-to-air node simulation is shown in Figure 28.

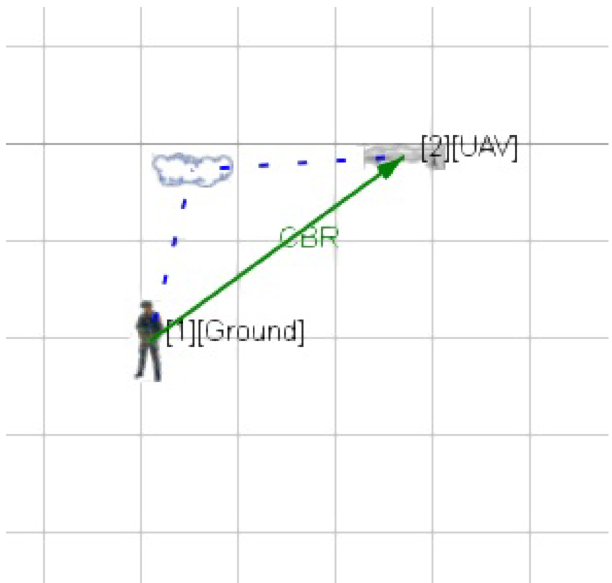

Figure 28. Simulation for a Ground-to-Air Node Using EXata. Source: [1].

2. EXata Simulation Properties

After the network architecture is created, the process establishes parameters for simulation. There are many settings that can be configured for the simulation to simulate the different operational scenarios and network parameters of interest.

Some network properties necessary for beginning a simulation are highlighted in the following paragraphs. In this thesis, we are primarily interested in the following simulation properties: Scenario Properties, Wireless Subnet Properties, and the Mobility Waypoint Editor.

Under the Scenario Properties window, the user configures the frequency, signal propagation speed, path loss, shadowing, and fading model for each channel in the network architecture. A screen capture of the scenario properties window is shown in Figure 29.

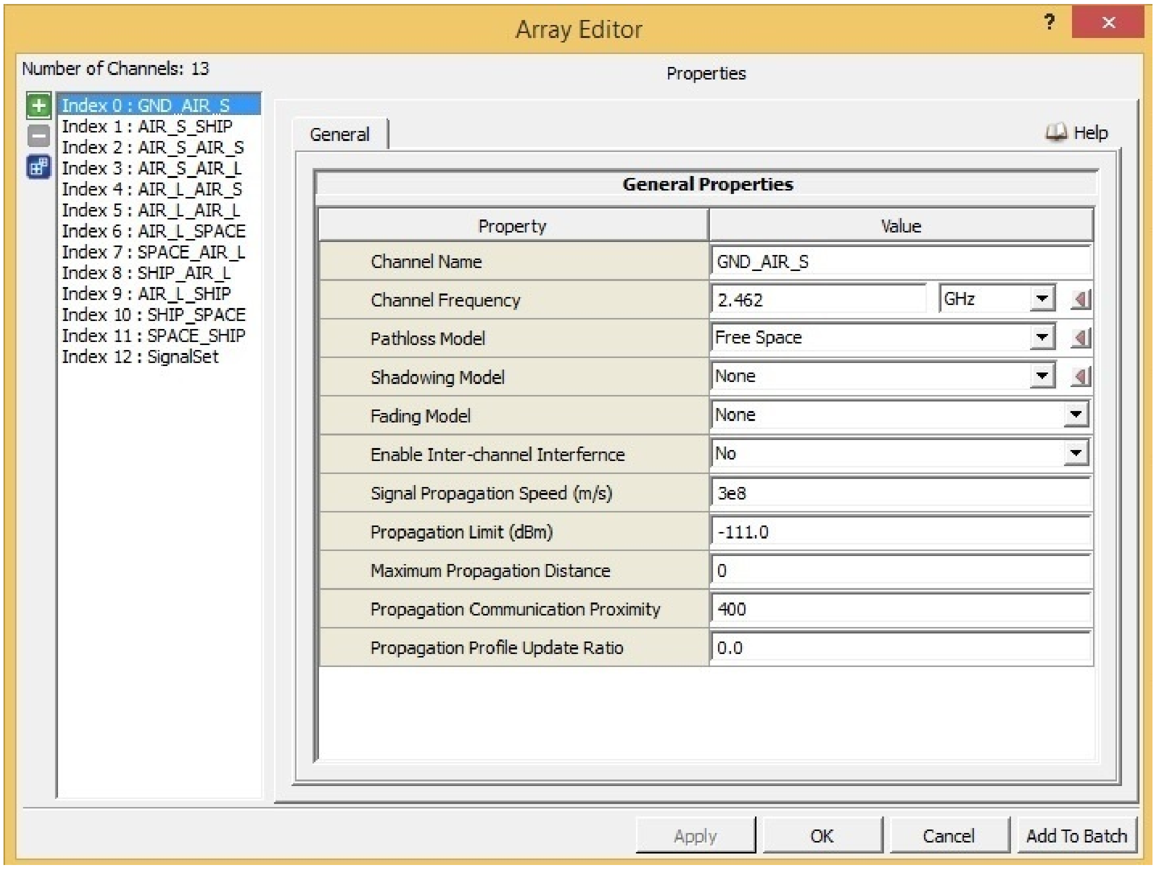

Figure 29. EXata's Scenario Properties Window. Source: [1].

The available options for channel properties are summarized in Table 13.

Table 13. Scenario Properties Selection

Property	**Value**
Path Loss Model	Two Ray/Free Space
Shadowing Model	Lognormal/Constant/None
Fading Model	Ricean/Rayleigh/Fast Rayleigh

Under the Wireless Subnet Properties window, users configure the radio type, data rate, transmission power, receiver sensitivity, antenna parameters (e.g., antenna model, gain, height, efficiency, and losses), temperature, and noise factor for each channel in the network architecture. A screen capture of this window is shown in Figure 30.

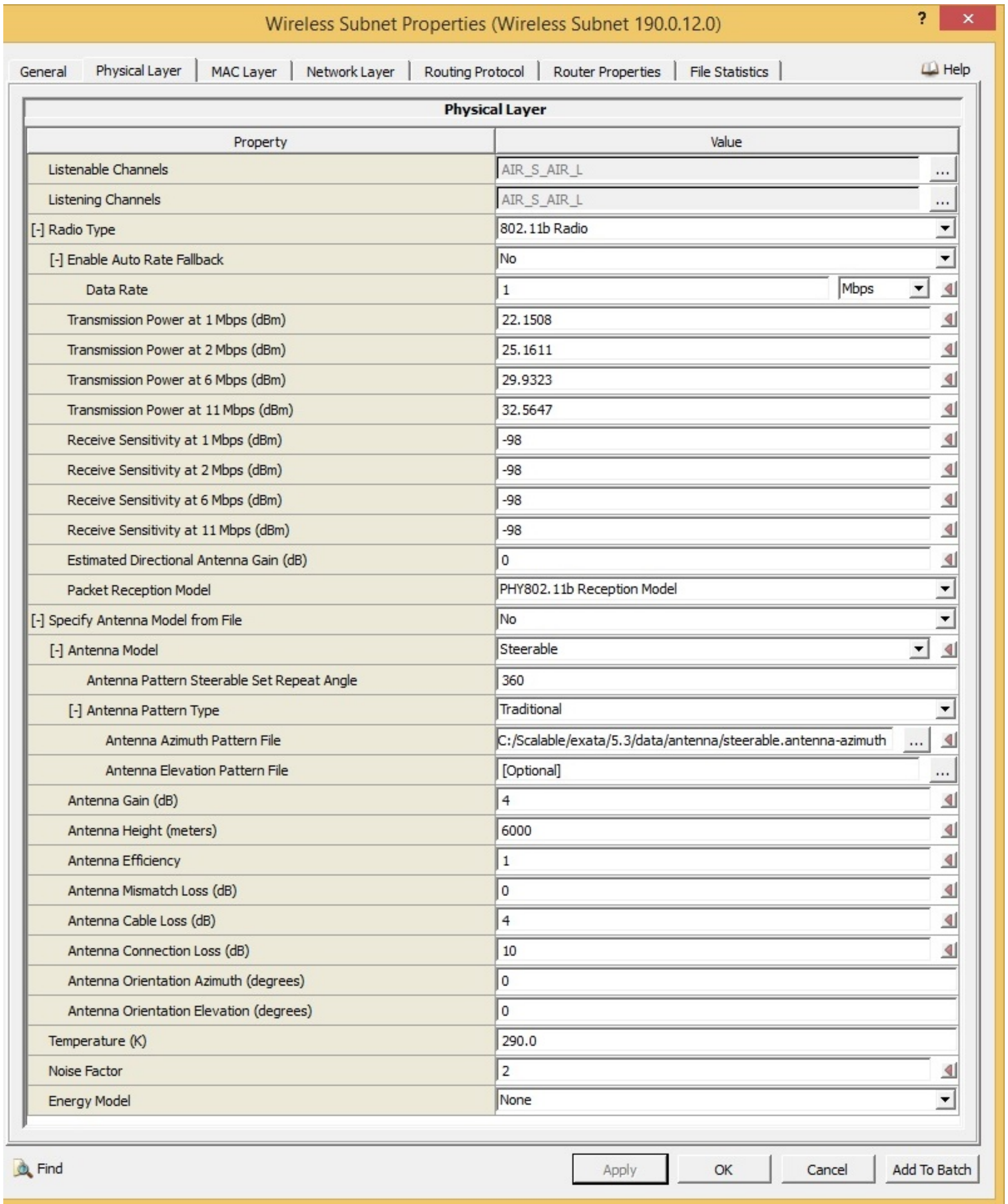

Figure 30. EXata’s Wireless Subnet Properties Window. Source: [1].

The wireless subnet in EXata software is a logical interface for connecting two or more nodes under a single subnet. The interface between these nodes can be a wired, wireless or microwave connection. A subnet cluster can be formed by associating the subnet with a channel or frequency. An example of the wireless subnet for the Air(S) and Air(L) nodes is illustrated in Figure 31.

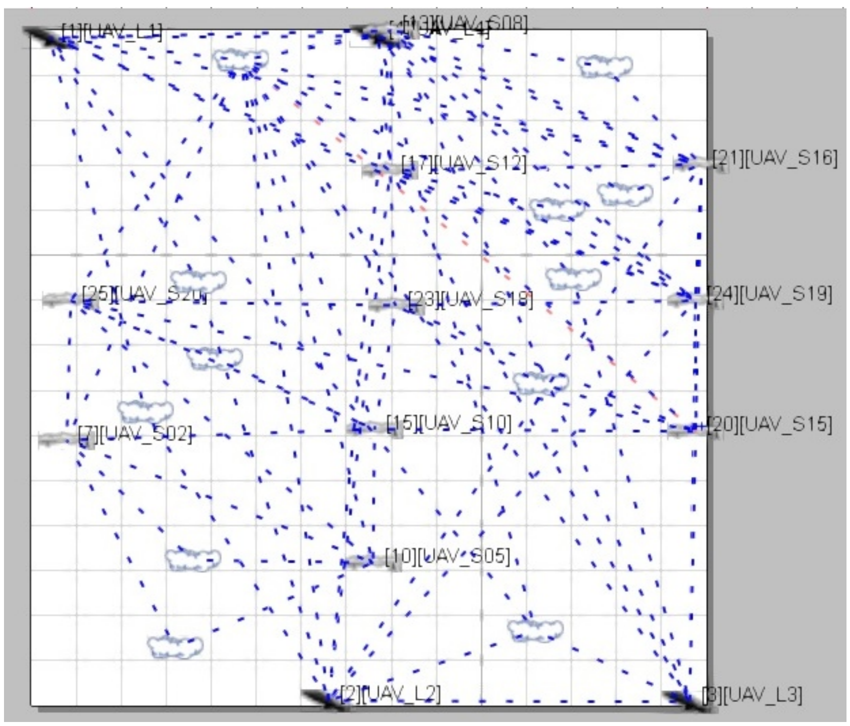

Figure 31. An Example of the Wireless Subnet for the Air-to-Air Nodes. Source: [1].

The design architecture for the air nodes is configured such that a pair of Air(S) nodes are connected in a cluster using a wireless subnet, and all the Air(S) nodes are connected to another wireless subnet cluster for information sharing among Air(S) nodes. A similar approach is adopted for the Air(L) nodes whereby two Air(L) nodes form a cluster and jointly connect to another wireless subnet cluster for information sharing among Air(L) nodes. Another wireless subnet jointly links the Air(S) and Air(L) nodes together for information relaying.

The wireless subnet connecting the CubeSat and a Ship or Air(L) node is configured as an abstract radio type using carrier-sense multiple access (CSMA) as the

MAC protocol to differentiate the CubeSat radio from the 802.11b radio types defined for the ground and air nodes.

Under the MAC Protocol and Routing Protocol tab, it is possible to configure the network using IEEE 802.11b MAC and DYMO routing protocols to minimize network congestion. In order to maintain connectivity with neighbors, the enable processing hello option under the DYMO routing protocol must be checked. The MAC propagation delay parameter is configured by calculating the delay using the distance over speed of light formula.

In addition, the coordinates toolbar is used to define the position and altitude in the Cartesian coordinate system of each device node. This information is used by the software to derive certain network parameters like the range and free-space path loss.

Under the Mobility Waypoint Editor window, users pre-program movements of the device nodes by specifying the starting coordinates, time to reach, and the ending coordinates in the network architecture. A screen capture of this window is shown in Figure 32.

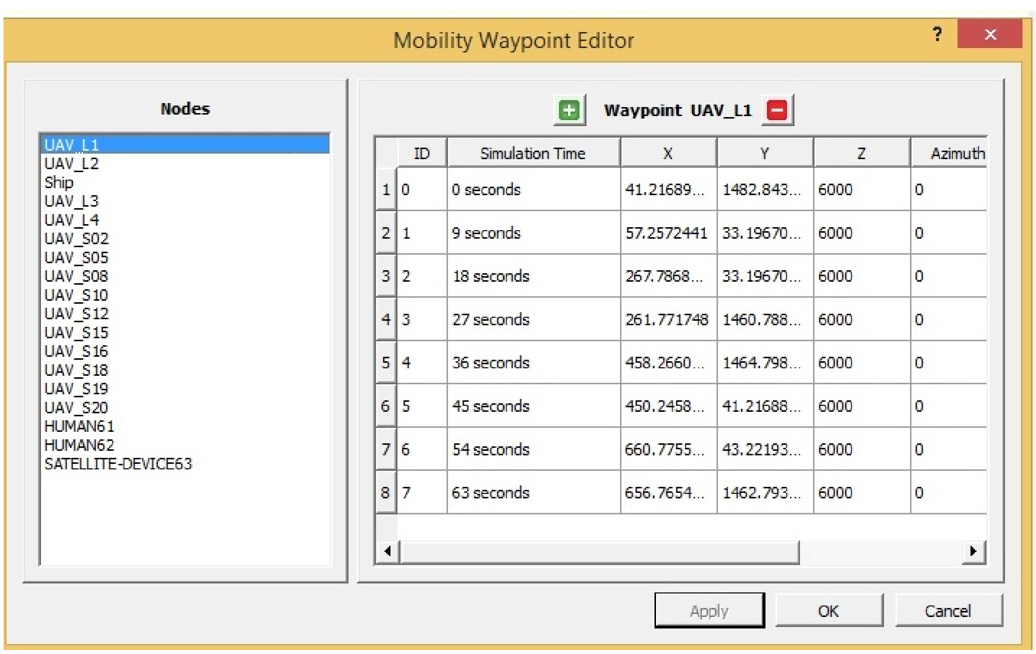

Figure 32. EXata's Mobility Waypoint Editor Window. Source: [1].

The mobility of the Air(L) nodes is illustrated in Figure 33.

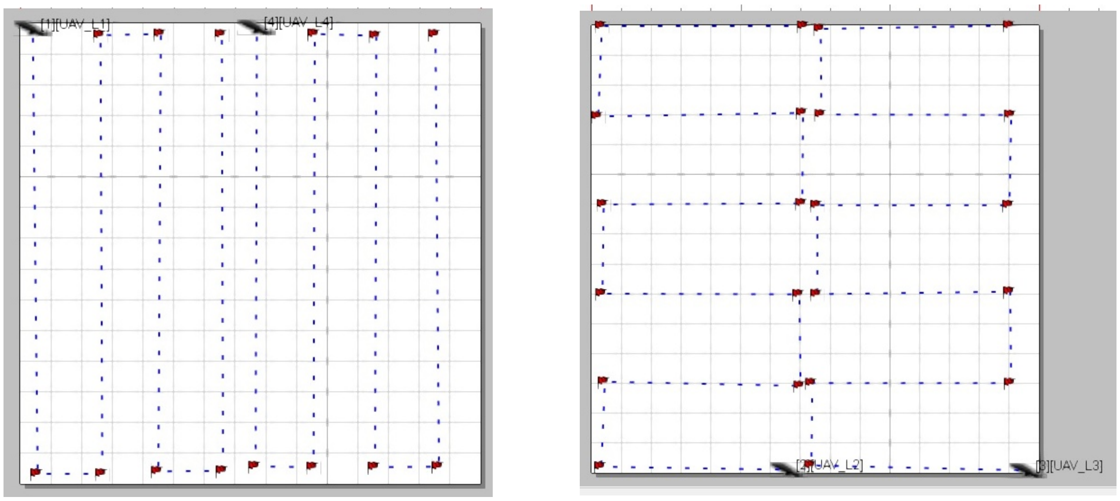

Figure 33. Mobility of the Air(L) Nodes. Source: [1].

The mobility of the Air(S) nodes is illustrated in Figure 34.

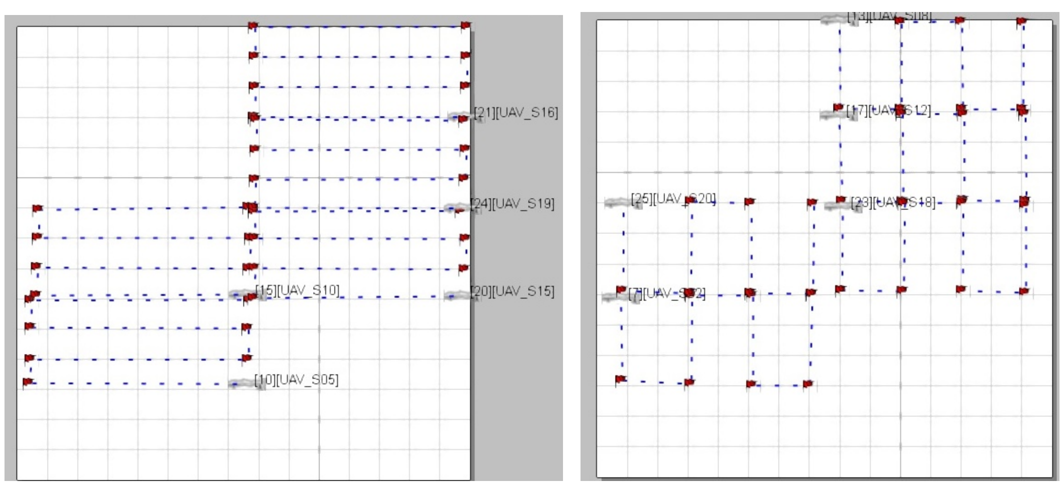

Figure 34. Mobility of the Air(S) Nodes. Source: [1].

3. EXata Simulation Model

In this section, we investigate whether a second layer air node such as Air(L) or third layer space node such as CubeSat can be used as a backbone to assist in eliminating the bottleneck wherein many nodes try to access the network for information exchange.

The intention is to add redundancy to the channel and minimize the packet loss due to network congestion and timeouts.

After the user incorporates the scenario properties, wireless subnet properties, and the mobility waypoint configuration for all nodes of the multi-tier architecture, the model is ready for the first simulation. The completed simulation model for EXata is shown in Figure 35.

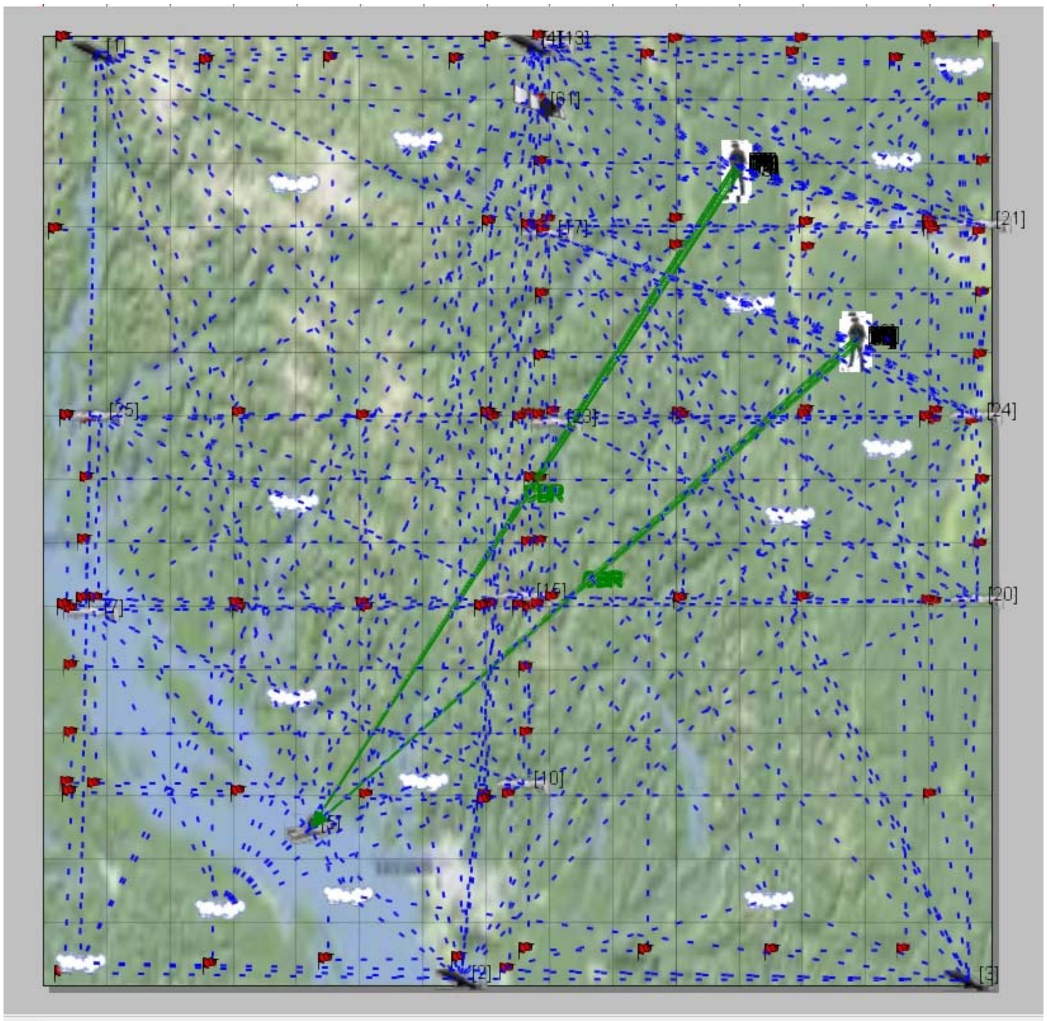

Figure 35. Simulation Model for EXata. Source: [1].

In addition, the coordinates toolbar can be used to dictate the position and altitude in a Cartesian coordinate system for each device node. This information is used by the software to derive certain network parameters like the range and free-space path loss.

In order to create a more realistic operational scenario, the EXata constant bit rate (CBR) generator is used to simulate data and network traffic from the ground nodes (17 to 46) to the sea node (6), respectively. The simulation settings for the traffic generator in EXata are shown in Table 14.

Table 14. CBR Generator Settings for EXata

Description	**Data Traffic (1.0, 5.5 and 11.0 Mbps)**	**Network Traffic (1.0 Mbps)**	**Network Traffic (5.5 Mbps)**	**Network Traffic (11.0 Mbps)**
Source Node ID	17 to 31	32 to 46	32 to 46	32 to 46
Destination Node ID	6	6	6	6
Start Time	0 s	0 s	0 s	0 s
Duration	67 s	67 s	67 s	67 s
Packets to Send	335	670	1340	1340
Packet Size	500 bytes	750 bytes	2250 bytes	4500bytes
Packet Interval	0.2 s	0.1 s	0.05 s	0.05 s
Packet per Second	5	10	20	20
Traffic per Source	20.1 kbps	60.1 kbps	360.3 kbps	720.5 kbps
Number of Sources	15	15	15	15
Equivalent Traffic	300.9 kbps	901.3 kbps	5.4 Mbps	10.8 Mbps

A total of 15 nodes are used to generate 300.9 kbps of data traffic in the operational scenario. Given the scenario, an additional 15 nodes are used to generate 0.9013, 5.4, and 10.8 Mbps of network traffic are added to the data traffic for the 1.0, 5.5, and 11.0-Mbps channel, respectively. The addition of data and network traffic into the channel creates a more realistic operational scenario.

V. OPERATIONAL SCENARIO SIMULATION

The operational scenario for the proposed multi-tier wireless network in the event of single-node or multiple-cluster failures are outlined in scenarios I to VI. The concept visualization presented in Chapter III is simplified into a model to illustrate the different operational scenario in the event of single-node or multiple-cluster failures. The simplified model is shown in Figure 36.

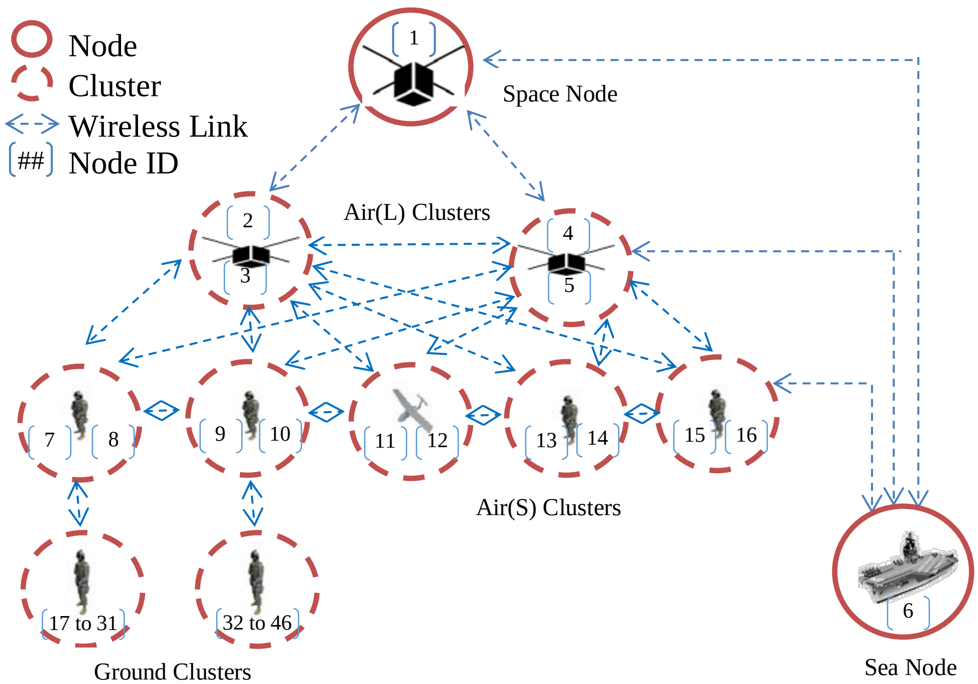

Figure 36. Simplified Model of the Operational Scenario. Adapted from [1].

The general concept of the simplified model is to highlight the interconnection between the nodes and clusters for the relay of data packets from the source to destination in accordance to the operational scenario. For example, the ground cluster wants to relay information to the sea node. This information relay to the distant sea node is achievable by routing through the Air(S) clusters.

A. SCENARIO I: AIR(S) CLUSTER

In this operational scenario, the ground cluster relays information to the sea node through the Air(S) clusters only. The visual representation for this scenario is shown in Figure 37. The data rate of 1.0 Mbps is used unless otherwise stated.

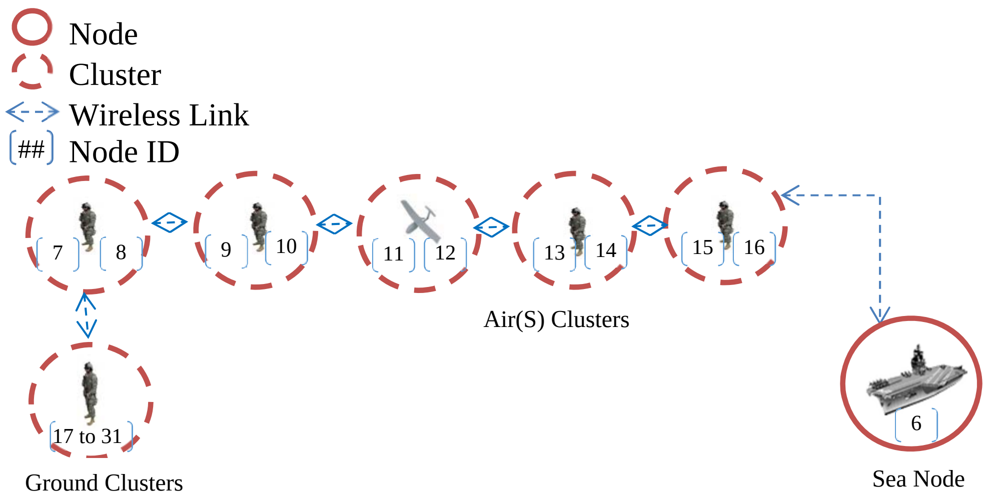

Figure 37. Operational Scenario I. Adapted from [1].

The purpose for this scenario is to ensure that the Air(S) cluster exhibits the relay of information from one cluster to the other in the simulation model. Network parameters like the average delay time, average jitter time, throughput, and packet loss are recorded for comparison with the subsequent scenarios.

It is expected that the ground node selects a path for the relay of information to the sea node. Information sharing within the cluster is allowed as long as the data traffic generated by the CBR generator at the ground cluster reaches the sea node. This scenario is performed using the channel properties for the 1.0 Mbps data rate and repeated for the 5.5 and 11.0 Mbps data rate. The EXata software tool is used to verify the simulation model and determine the network parameters.

1. Simulation Result for Scenario I

EXata simulation provides a visualization of the data traffic routing through the nodes with a moving green arrow from node to node. A screen capture during the simulation is shown in Figure 38.

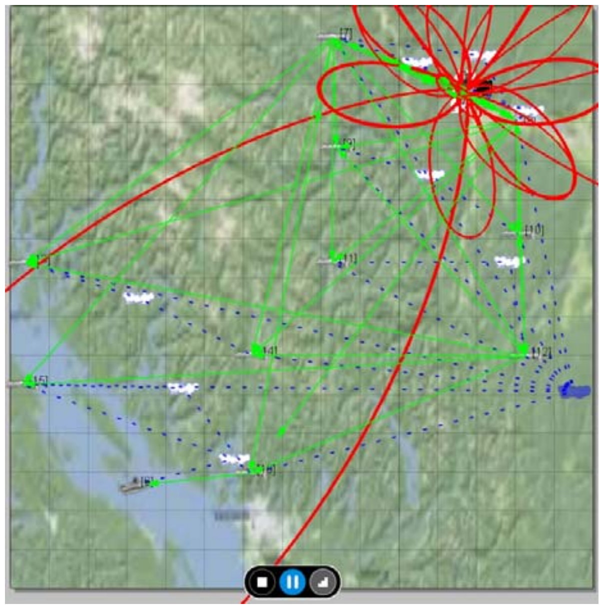

Figure 38. Data Traffic Routing in EXata Simulation. Source: [1].

The simulation results generated by EXata were used to determine the routing of data packets in the simulation model using the parameters such as data bytes forwarded and received. The result up to nodes 16 is shown in Figure 39.

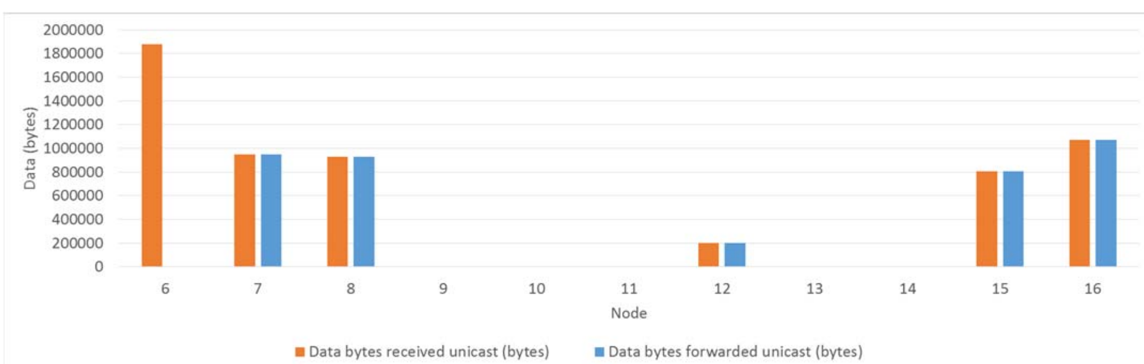

Figure 39. Data Bytes Forwarded and Received by Individual Nodes

The output of the simulation results help to identify the routing path taken by the data traffic generated by the CBR generator from the ground node to sea node. It is observed that the data traffic follows a routing path through nodes 7, 8, 12, 15, and 16 before reaching the destination Node 6.

The average delay is a measure of time it takes for the message to reach the destination. The simulation result is shown in Figure 40.

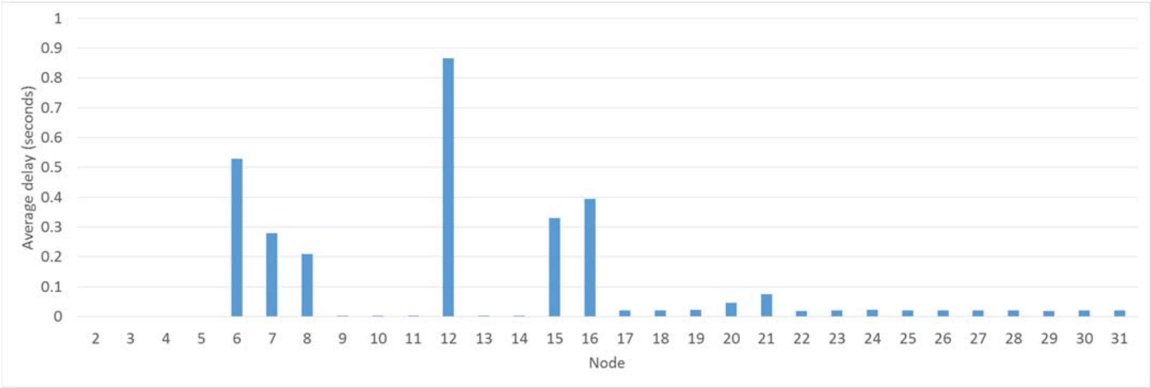

Figure 40. Average Delay Time up to Node 31

The average jitter is a measure of time difference in the inter-arrival time of packets caused by network congestion, timing drift or route changes. The simulation result is shown in Figure 41.

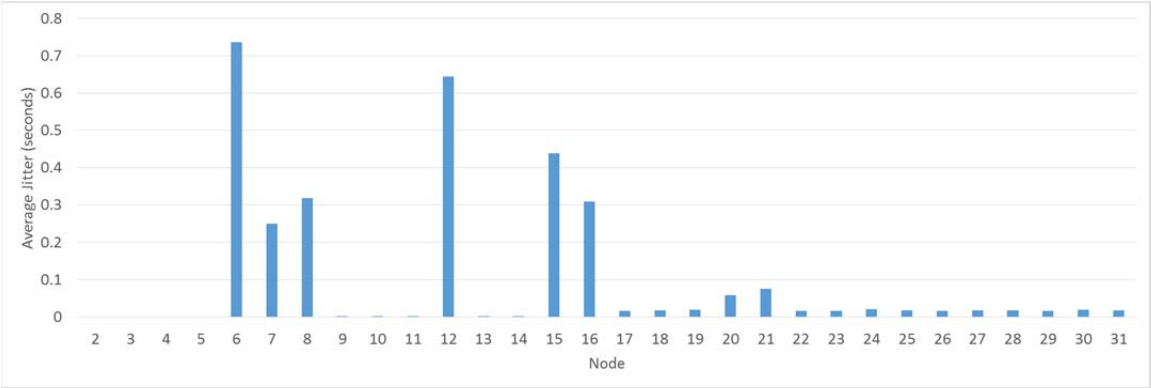

Figure 41. Average Jitter Time up to Node 31

The average delay and jitter time from scenario I are compared with the results from scenario II to analyze the network performance of the simulation model representing the multi-tier network architecture in the presence of data traffic.

Throughput is a network session parameter that determines the total number of bits sent to the destination node over a time difference between the first and the last packet that is successfully sent. The throughput results extracted from the destination Node 6 for source nodes 17 to 31 is shown in Figure 42. The 15 columns of throughput values corresponds to the 15 source nodes simulating data traffic using CBR generators. We assume that each column of the throughput result corresponds to one source generating CBR data traffic to the destination node.

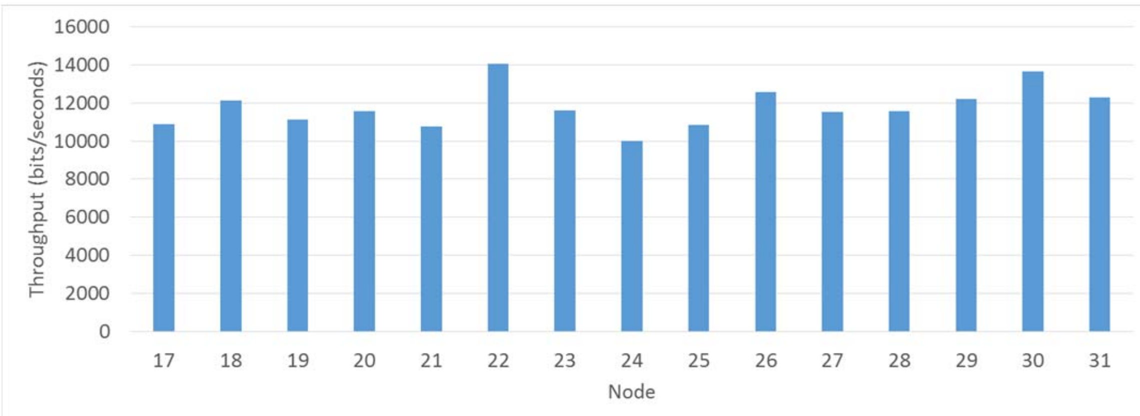

Figure 42. Throughput at Destination Node 6

Although a similar configuration is used for the CBR traffic generators, some nodes may experience a lower throughput as compared to their counterparts. The main contribution for such a difference is due to the varying range and the noise characteristics of the communication channel between two moving air nodes.

The communication range between two nodes may increase or decrease depending on the pre-programmed waypoint for each node. A situation may occur when two air nodes are located at an increased communication range, and a higher energy per bit E_b is required to overcome this increase; however, neither the signal power nor data rate is increased to sustain the link. As a result, the data packet experiences a higher bit error probability, meaning more errors at the receiver. This error results in a packet drop or retransmission request issued by the destination node to the source node to resend the data packet. In the event that the network is congested and the request for retransmission has reached its limit, the data packet is dropped; thus, the throughput for the source nodes is reduced.

Total packet drop is a counter that counts the total number of packet drops due to retransmission limit. The total packet drops up to Node 31 using the 1.0 Mbps data rate are shown in Figure 43. We observed a bottleneck situation at the interface between the ground nodes (i.e., Nodes 17 through 31) generating data traffic to the intermediate Air(S) cluster (i.e., Node 7 and 8). This results in a drop of data packets caused by exceeding the retransmission limit.

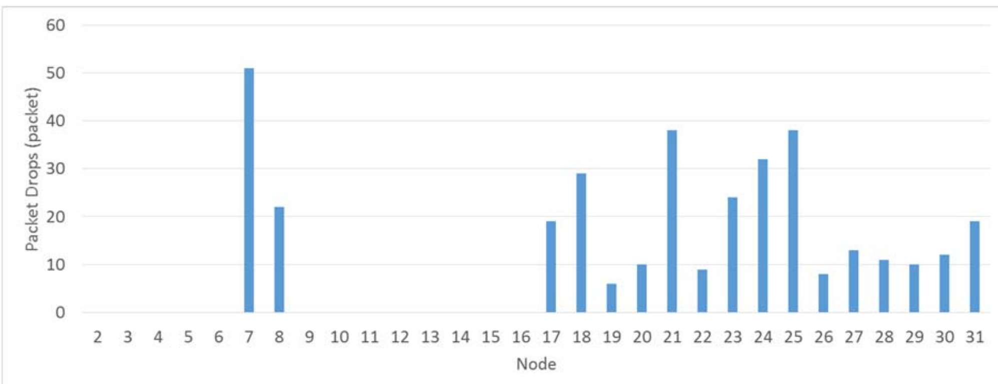

Figure 43. Total Packet Drops up to Node 31

The simulation result of the total packet drops up to Node 31 using 1.0, 5.5, and 11.0 Mbps data rates is consolidated in Figure 44.

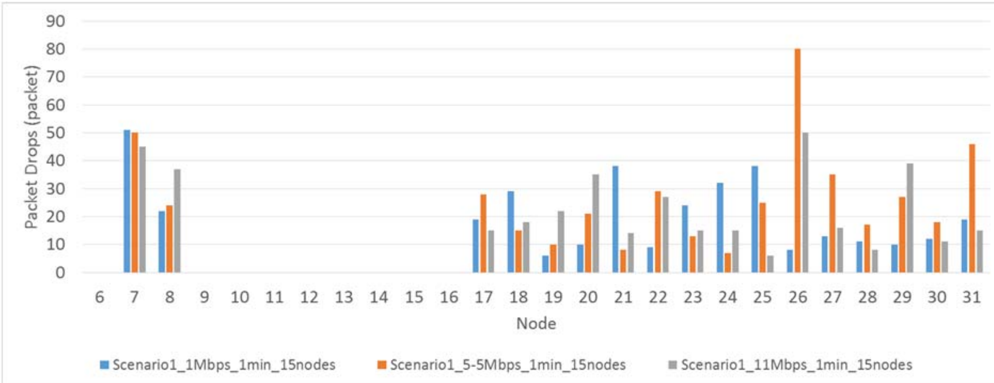

Figure 44. Total Packet Drop up to Node 31

We observed that the increase in data rate for scenario I does not reduce packet drops since the energy per bit is inversely proportional to the data rate. This means that for a given signal power, the increase in data rate decreases the energy per bit, which in turn reduces the SNR per bit. A reduced SNR per bit causes a higher bit error probability that increases the number of errors in the data packet reception. The error checking protocol detects and demands retransmission, resulting in an increase in drops of data packet due to exceeding the retransmission limit. This occurrence also reduces the throughput measured at the destination node.

The EXata simulation is repeated for the 5.5 and 11.0 Mbps data rates, and the simulation results are consolidated in Appendix B. We observe that the increase in data rates reduces the throughput since the energy per bit is inversely proportional to the data rate. The overall SNR per bit is reduced, and the bit error probability increases. This results in more transmission errors that lead to more data packet drops and more data packet retransmission at the destination node.

We conclude that the simulation model for scenario I predicts information is relayed from the source to the destination node with a noticeable bottleneck situation for all ground-to-air node interfaces.

B. SCENARIO II: AIR(S) CLUSTER WITH NETWORK TRAFFIC

In this operational scenario, the objective is for the ground cluster to relay information to the sea node through the Air(S) clusters in the presence of simulated network traffic generated by a separate ground cluster. The visual representation for this scenario is shown in Figure 45. The data rate of 1.0 Mbps is used unless otherwise stated.

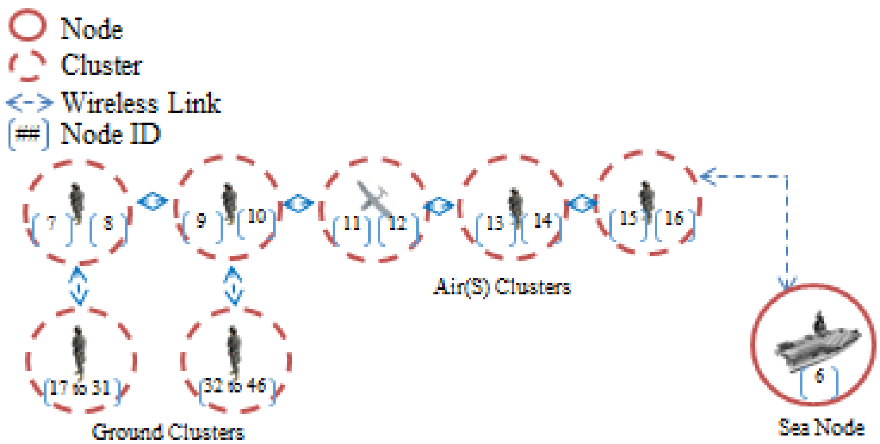

Figure 45. Operational Scenario II. Adapted from [1].

The purpose of this scenario is to assess the handling of information when routing through the Air(S) clusters in the presence of a simulated network traffic generator from a separate ground cluster to a sea node.

Network parameters like the average delay time, average jitter time, throughput, and packet loss are recorded and compared to operational scenario I.

Heavier network traffic at the Air(S) clusters as well as longer delays and jitter durations are expected at these clusters. The throughput at each source nodes will also decrease due to the additional network traffic forming up at each node. Similarly, information sharing within the cluster is allowed as long as the information generated by the ground node or cluster reaches the sea node. The EXata software tool is used to verify the simulation model and determine the network parameters.

1. Simulation Result for Scenario II

The simulation results generated by EXata are used to determine the routing of information in the simulation model using the parameters of data bytes forwarded and received. The result up to Node 16 is shown in Figure 46.

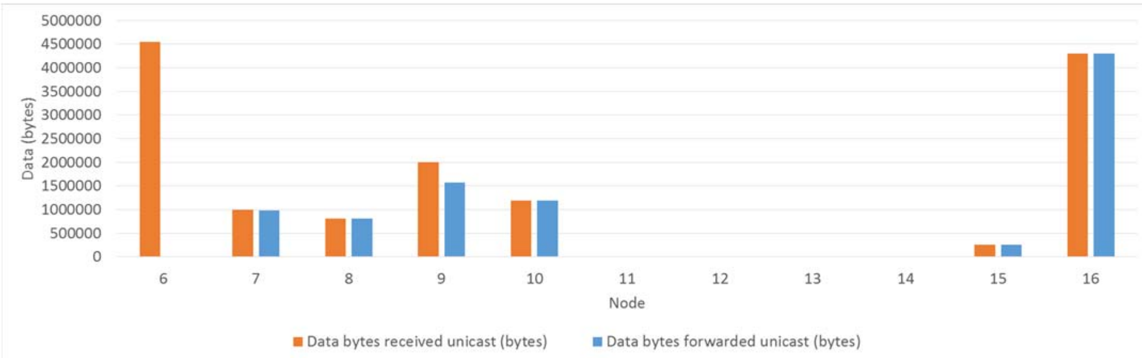

Figure 46. Data Bytes Forwarded and Received by Individual Nodes

The simulation results indicate that the main bulk of traffic follows a routing path through nodes 7, 8, 9, 10, 15, and 16 before reaching the destination Node 6. The average delay up to Node 31 is shown in Figure 47.

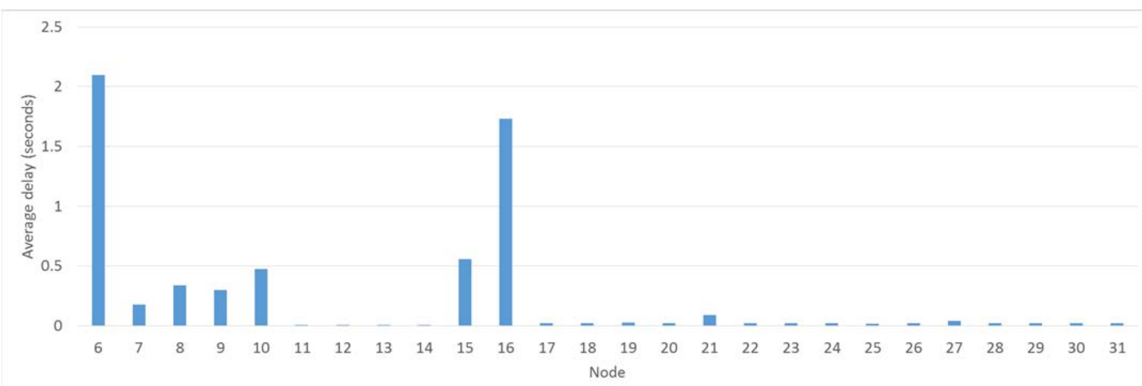

Figure 47. Average Delay Up to Node 31

The simulation result for the average unicast jitter up to Node 31 is shown in Figure 48.

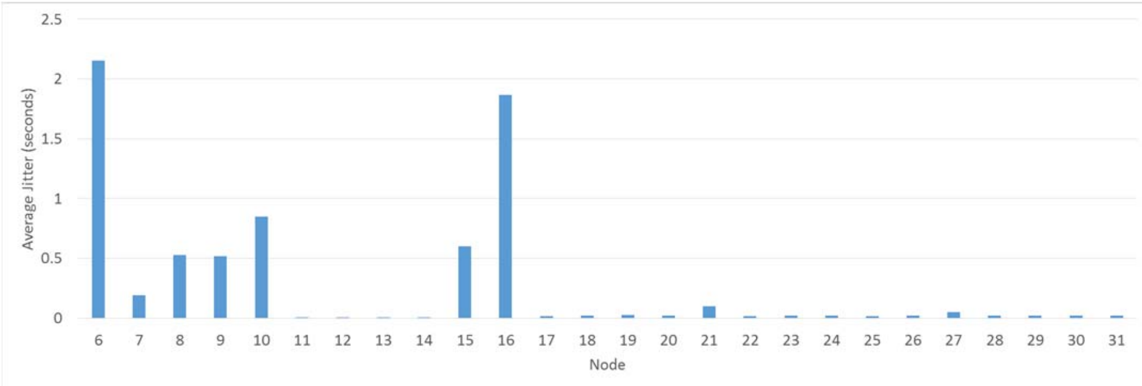

Figure 48. Average Jitter Up to Node 31

The throughput results extracted from the destination Node 6 for source nodes 17 to 46 is shown in Figure 49. The 30 columns of throughput values correspond to the 15 source nodes generating data traffic and 15 source nodes generating network traffic using CBR generators.

We observed a similar trend for the throughput when compared to scenario I. The main reasons for the lower throughput are varying range and the noise characteristics of the communication channel between two moving air nodes.

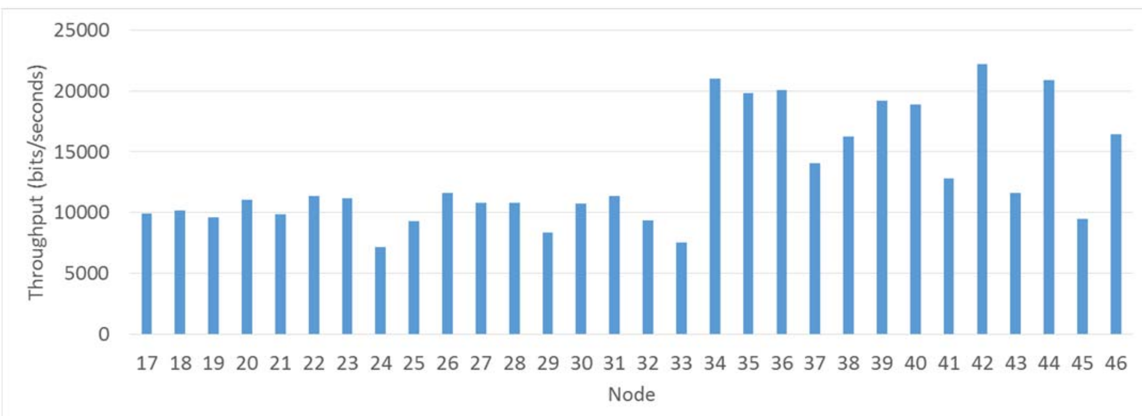

Figure 49. Throughput at Destination Node 6

The simulation result for the total packet drops up to Node 46 using 1.0 Mbps data rate is shown in Figure 50. A similar bottleneck and data packet drop situation is noticeable for all ground to air interfaces. The cause for the packet drops is due to the consolidation of data and network traffic from multiple interconnecting interfaces into the Air(S) nodes. This congestion of traffic at the Air(S) node increases the data packet processing time and may exceed the maximum allowable time duration to be deemed as successful data packet delivery to the destination node. The destination node demands retransmission of the data packet when the maximum allowable time duration is exceeded until the retransmission limit is reached. Thereafter, the data packet is dropped.

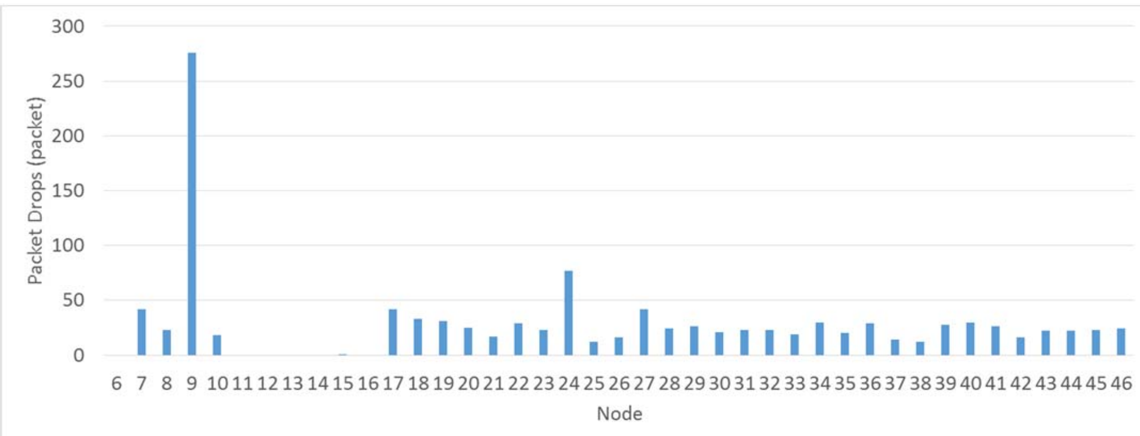

Figure 50. Total Packet Drops Up to Node 46

The simulation result of the total packet drops for different data rates up to Node 46 using 1.0, 5.5, and 11.0 Mbps data rates is consolidated in Figure 51.

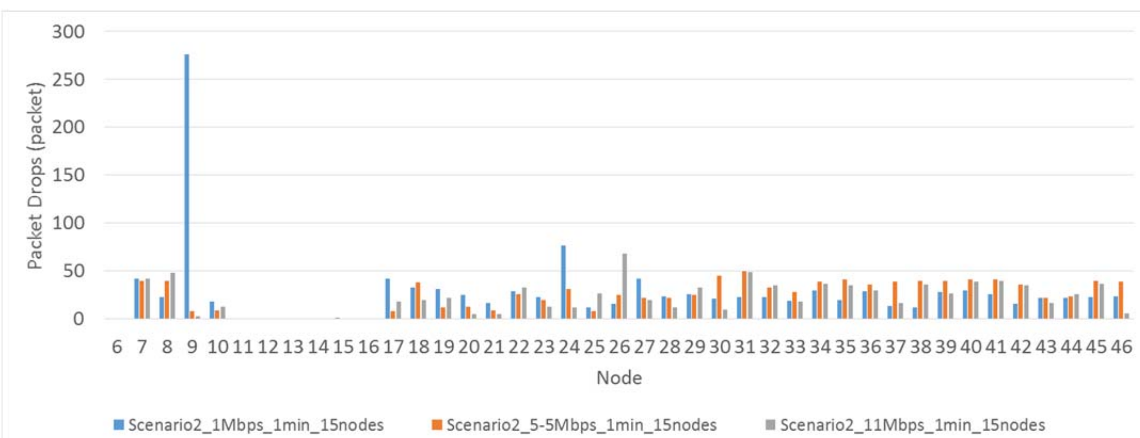

Figure 51. Total Packet Drops for Different Data Rate

In this scenario, we observe that the average end-to-end delay for each node generating CBR data traffic to the destination node increases up to 4.54 s in the presence of network traffic. This additional end-to-end delay time is due to the network traffic generating data packets at shorter time intervals. Since there are more data packets entering and leaving each node, the time required for one data packet to arrive at the destination node increases due to packet handling and queuing system at each node. The affect of network traffic on the average end-to-end delay time for the 15 nodes simulating data traffic in scenario I and II is shown in Figure 52.

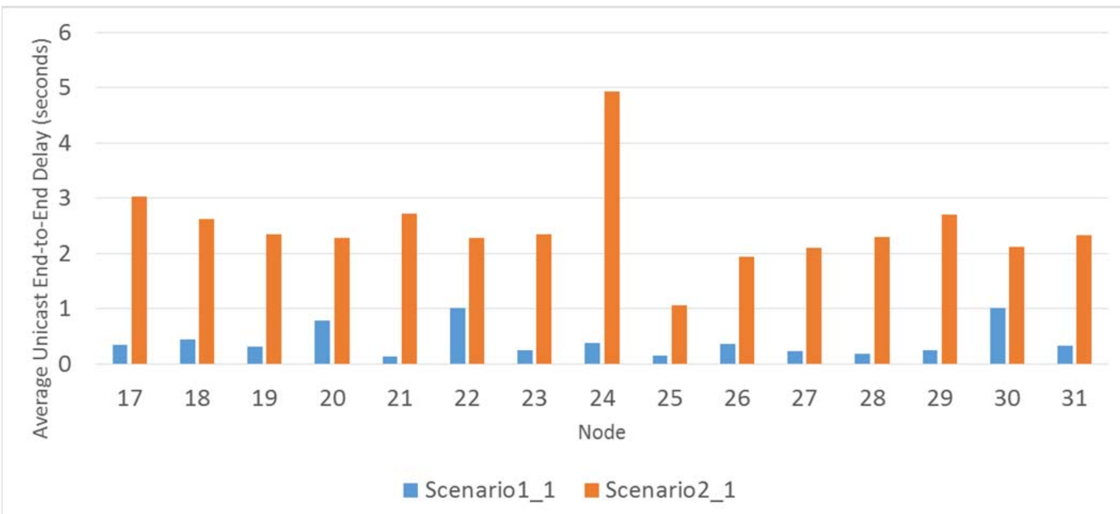

Figure 52. Average End-to-End Delay for Scenario I and II

The average unicast jitter is increased up to 0.2 s for the scenario whereby network traffic is present. The data packets generated by the network traffic at shorter time intervals populates the channel before the data packets generated by data traffic arrive at the intermediate node; hence, the average unicast jitter, which is a time measurement of inter-arrival time for the data packets, for the source node generating data traffic is increased since these data packets take a longer time duration to arrive at the destination node due to traffic congestion in the channel. The affect of network traffic on the average unicast jitter for the 15 nodes simulating data traffic in scenario I and II is shown in Figure 53.

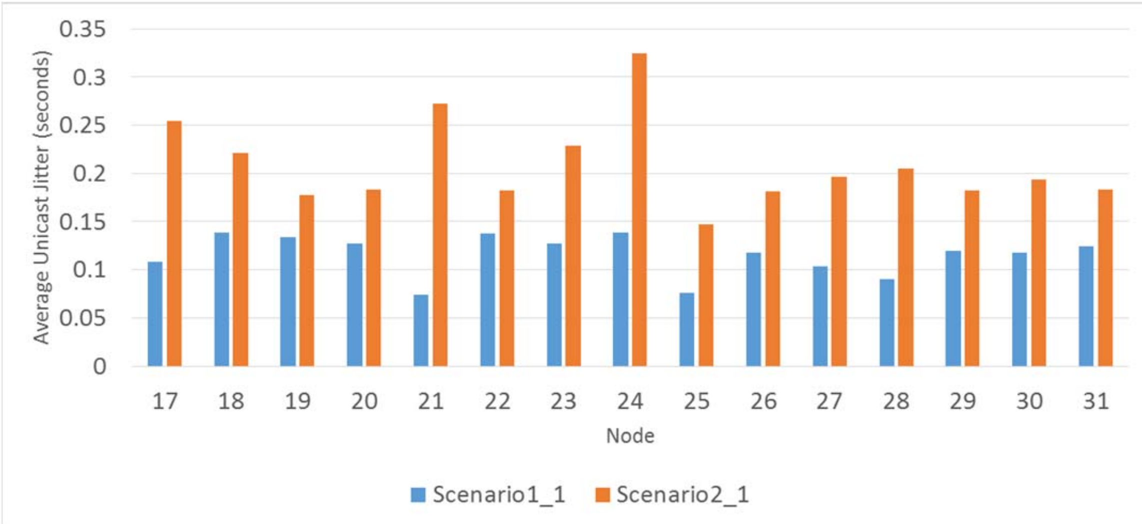

Figure 53. Average Jitter Time Comparison for Scenario I and II

The unicast received throughput is reduced up to 3870 bits per second in the presence of network traffic. The reason for the decrease is due to traffic congestion in the channel which affects the number of data packets that are successfully delivered to the destination node within the simulation time. The effect of network traffic on the throughput for the 15 nodes simulating data traffic in scenario I and II is shown in Figure 54.

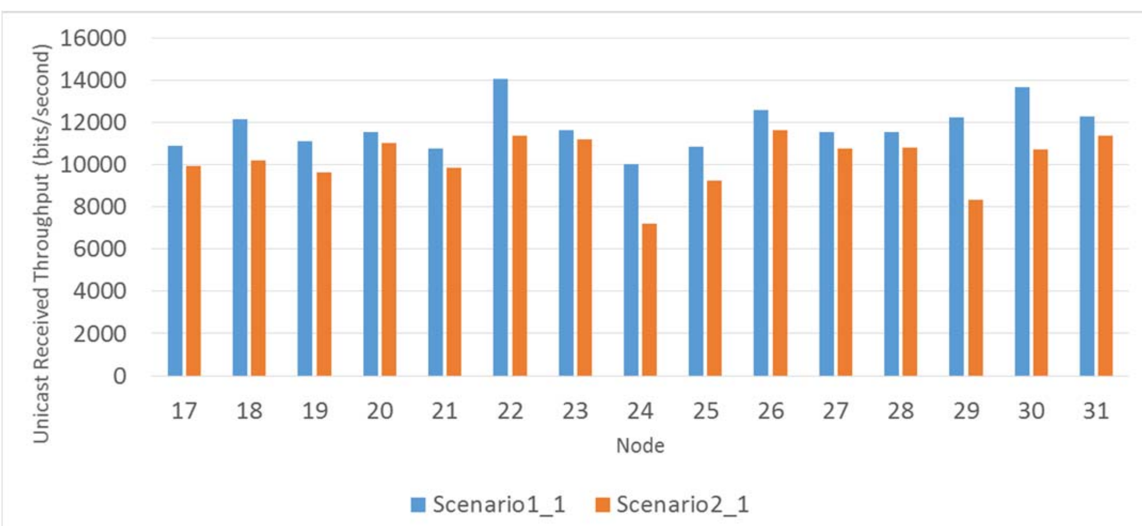

Figure 54. Throughput Comparison for Scenario I and II

In the simulation using 5.5 and 11.0-Mbps data rates for the channel, we observe that the received throughput is comparable for both data rates. This can be seen in Figures 55 and 56.

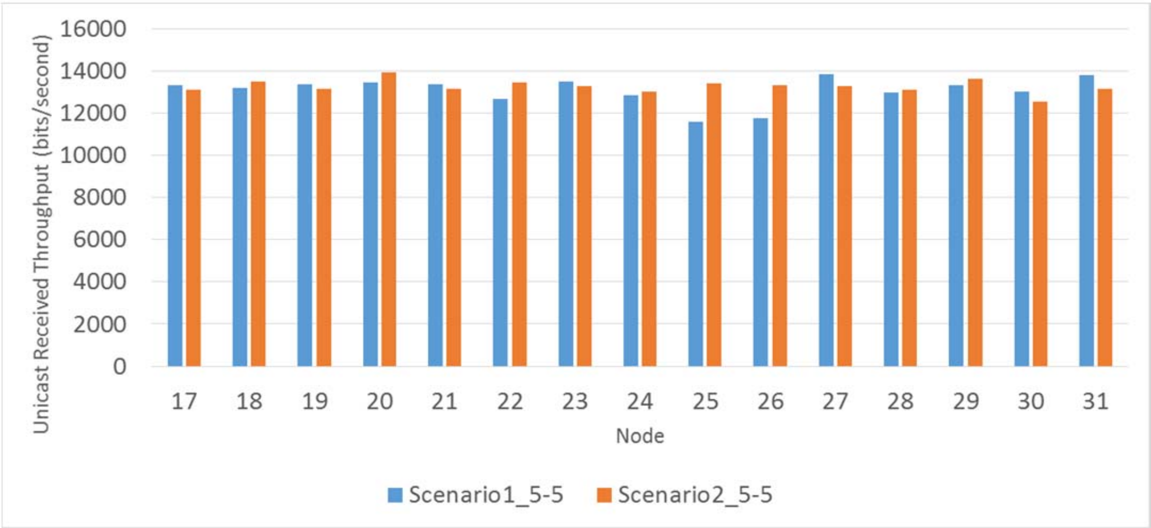

Figure 55. Throughput for Scenario I and II using 5.5 Mbps Data Rate

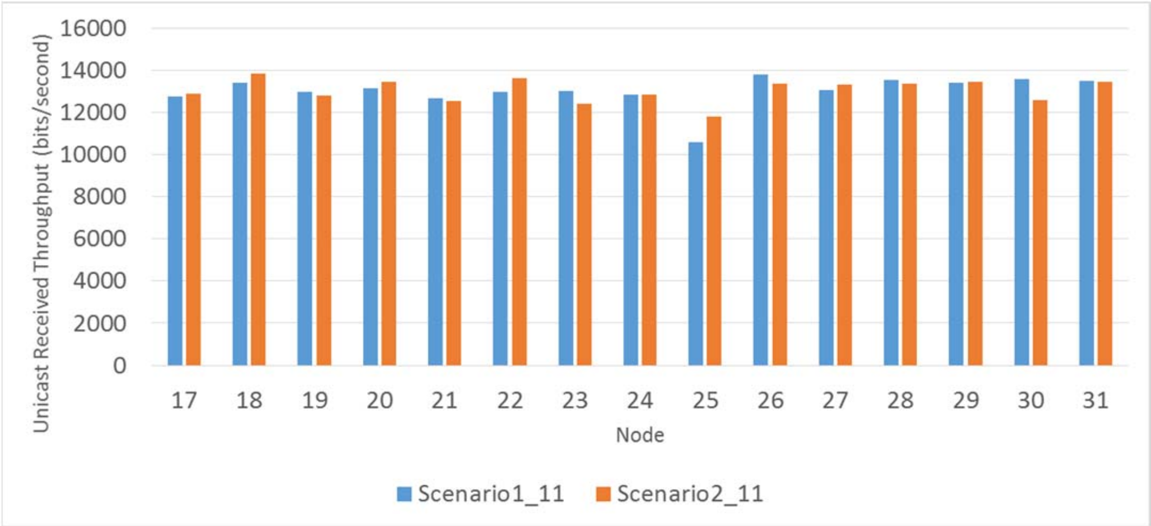

Figure 56. Throughput for Scenario I and II using 11.0 Mbps Data Rate

The reason for such a phenomenon is due to the configuration of the CBR generator at the source nodes. The CBR generators are configured such that the data traffic remains constant while the network traffic increases in order to populate the channel with traffic. Since the network traffic generates data packets at a shorter interval than the data traffic, there are more data packets generated from the network traffic arriving at each node, and it takes a longer time for the data traffic to arrive at the destination node due to congestion at these nodes. Eventually, the data traffic reaches the destination node before the end of simulation.

In order to demonstrate the effect of jamming using network traffic, we doubled the network traffic for the scenario II operating at 5.5-Mbps data rate. The unicast received throughput result under the more intense network traffic (labelled as Scenario2_5-5A) is shown in Figure 57.

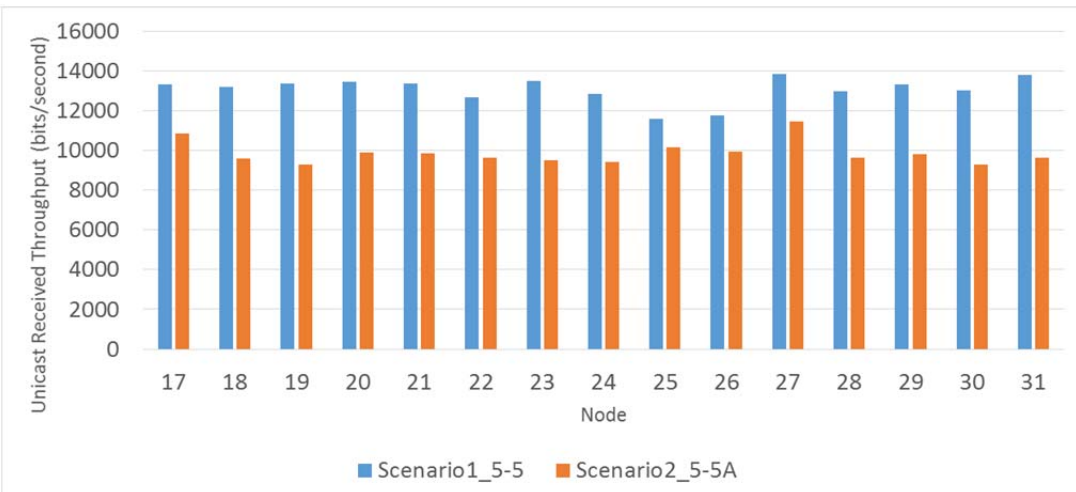

Figure 57. Throughput Comparison Using Doubled Network Traffic

This observation suggests that the unicast received throughput is affected by the intensity of network traffic in the channel. By doubling the network traffic, a reduction in unicast received throughput results, which is in line with the formula for determining throughput based on the total number of bytes received over the time difference between the last and first messages arriving at the node.

We observe that the average end-to-end delay and unicast jitter duration are higher than the simulation results obtained in scenario I. This is caused by the additional network traffic generated by the 15 nodes in a separate ground cluster.

C. SCENARIO III: AIR CLUSTERS

In this operational scenario, a layer of Air(L) clusters is added to the simulation model to provide redundancy for the multi-tier network architecture. The Air(L) clusters serve an identical purpose to that of the Air(S) clusters that relay information from a ground cluster to a sea node.

During the simulation, three Air(S) clusters that are formed by pairing nodes 11 and 12, 13 and 14, 15 and 16 are disabled at an elapsed time of 10.0 s. The visual representation for this scenario is shown in Figure 58. The data rate of 1.0 Mbps is used unless otherwise stated.

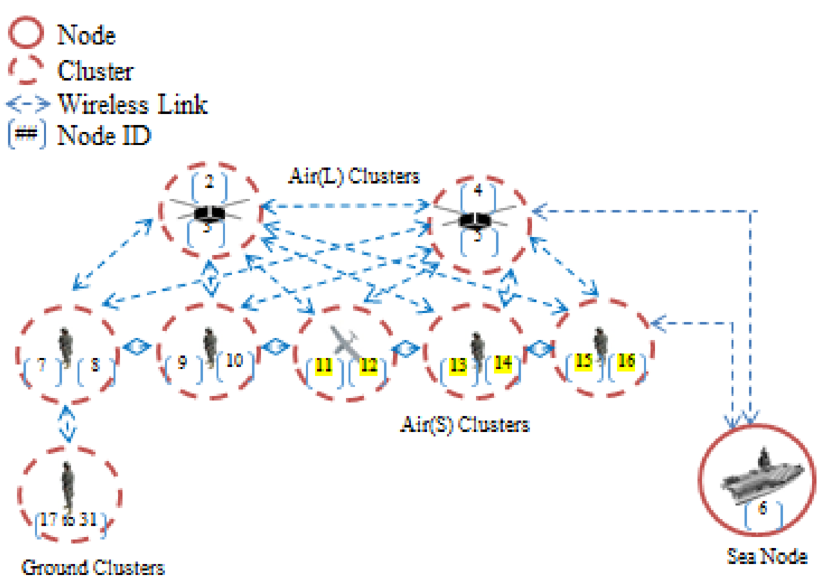

Figure 58. Operational Scenario III. Adapted from [1].

The purpose of this scenario is to determine whether the simulation model is robust enough to select an alternative path to relay the information from the ground cluster to the sea node in the event of a node or cluster malfunction. This is to replicate an operational scenario in which a node is intentionally removed by adversaries or by an unforeseen technical error, resulting in a loss of a node from the network.

Nodes 11, 12, 13, 14, 15, and 16 are deactivated 10.0 s into the simulation to simulate the situation whereby these nodes malfunction and the data traffic has to search for an alternative route to reach the destination node. Network parameters like the average delay time, average jitter time, throughput, and packet loss are recorded.

It is expected that the data traffic is routed through the Air(L) clusters after the Air(S) clusters have malfunctioned. A longer average end-to-end delay and unicast jitter duration is incurred due to this rerouting process. The EXata software tool is used to verify the simulation model and determine the network parameters.

1. Simulation Result for Scenario III

The simulation results generated by EXata are used to determine the routing of information in the simulation model using parameters such as data bytes forwarded and received. The result up to Node 16 is shown in Figure 59.

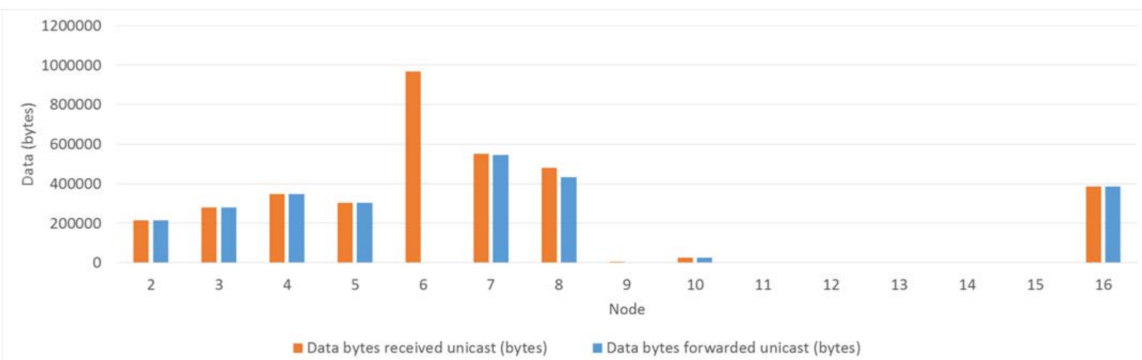

Figure 59. Data Bytes Forwarded and Received by Individual Nodes

The simulation results show that the data traffic generated by the CBR generator from the ground node to sea node follows a routing path through nodes 2, 3, 4, 5, 7, 8, 10, and 16 before reaching the destination Node 6. The simulation result may suggest Node 16 as the routing path for the data packets, but the data packets entering and leaving Node 16 happened before the node was deactivated 10.0 s into the simulation.

The simulation result for the average end-to-end delay, unicast jitter and total packet drops up to Node 31 are shown in Figures 60 to 62. These results are used to compare with those obtained from scenario IV to analyze the network performance of the multi-tier network architecture in the presence of network traffic.

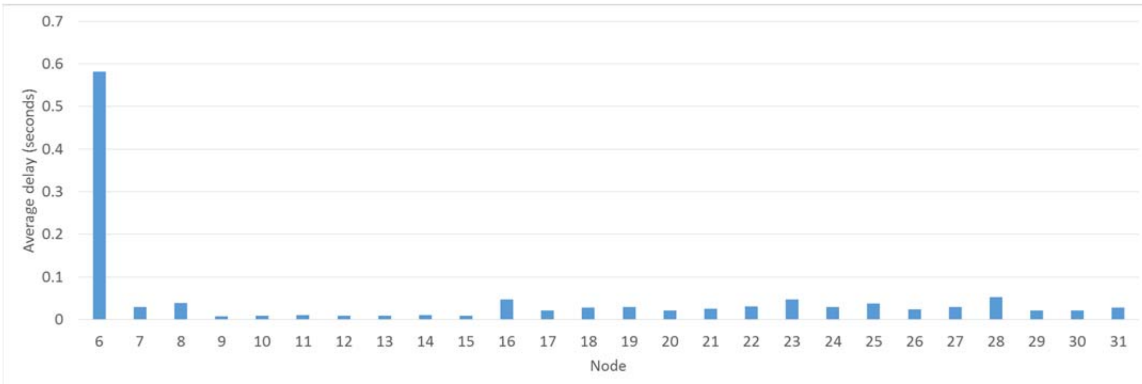

Figure 60. Average Delay Up to Node 31

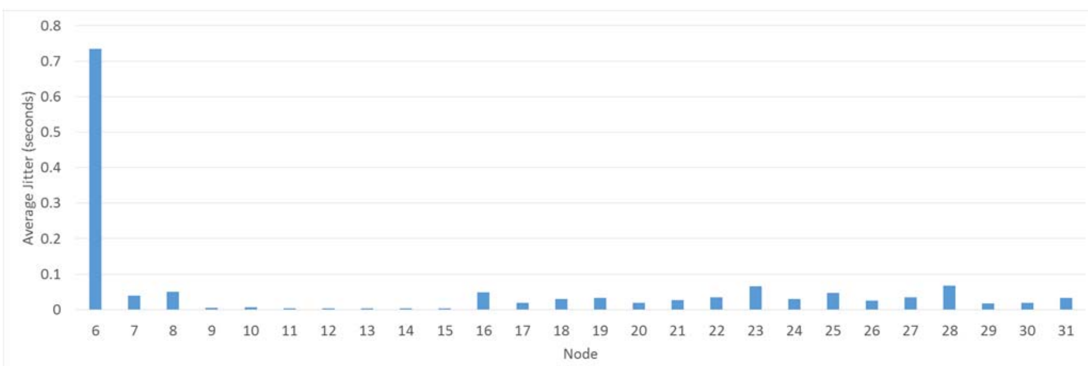

Figure 61. Average Jitter Up to Node 31

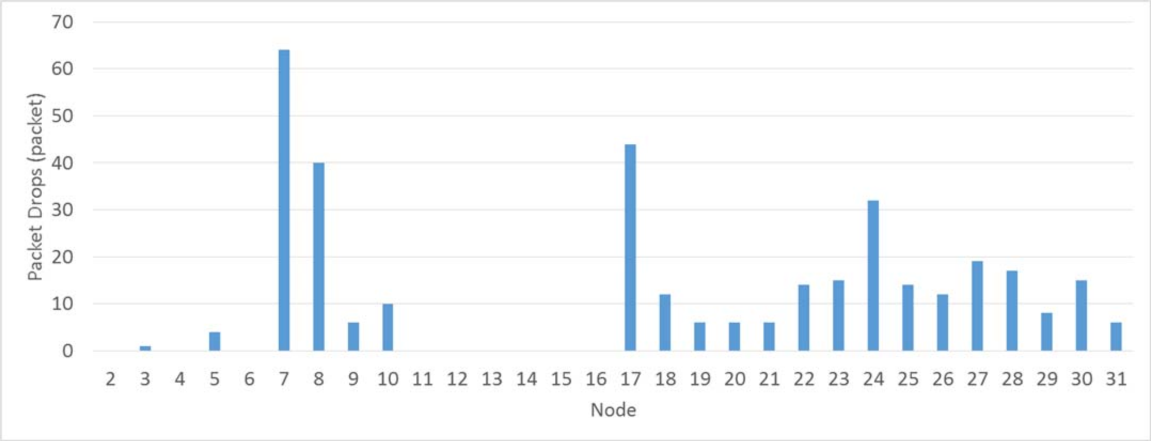

Figure 62. Total Packet Drops Up to Node 31

The throughput parameter extracted from the simulation result at destination Node 6 for source nodes 17 to 31 is shown in Figure 63.

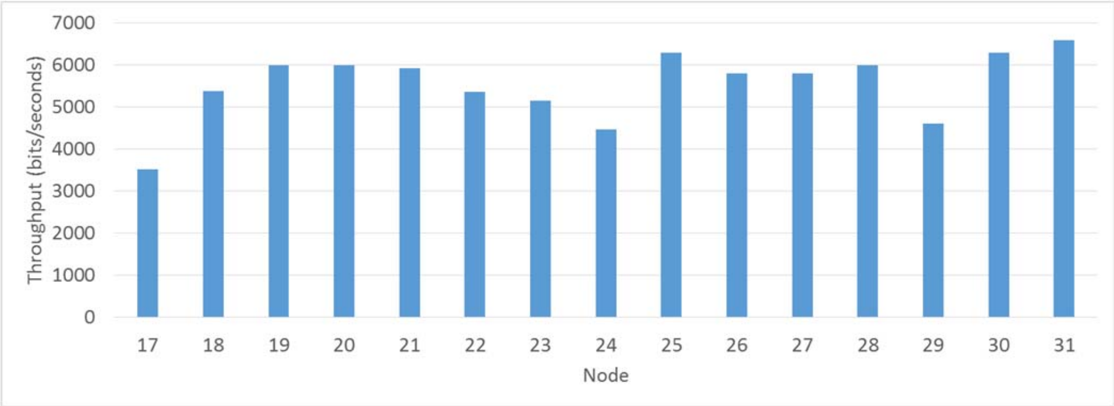

Figure 63. Throughput at Destination Node 6

The reason for lower throughput at destination Node 6 for scenario III is similar to the earlier operational scenario whereby the network was congested and the request for data packet retransmission had reached its limit; thus, the throughput for the source nodes is reduced.

We conclude that the simulation results for scenario III demonstrate that the traffic to the Air(L) clusters in the event of deactivated nodes or clusters will be rerouted.

D. SCENARIO IV: AIR CLUSTERS WITH NETWORK TRAFFIC

In this operational scenario, the ground cluster relays the information to the sea node through the air clusters in the presence of simulated network traffic generated by a separate ground cluster. The visual representation for this scenario is shown in Figure 64. The data rate of 1.0 Mbps is used unless otherwise stated.

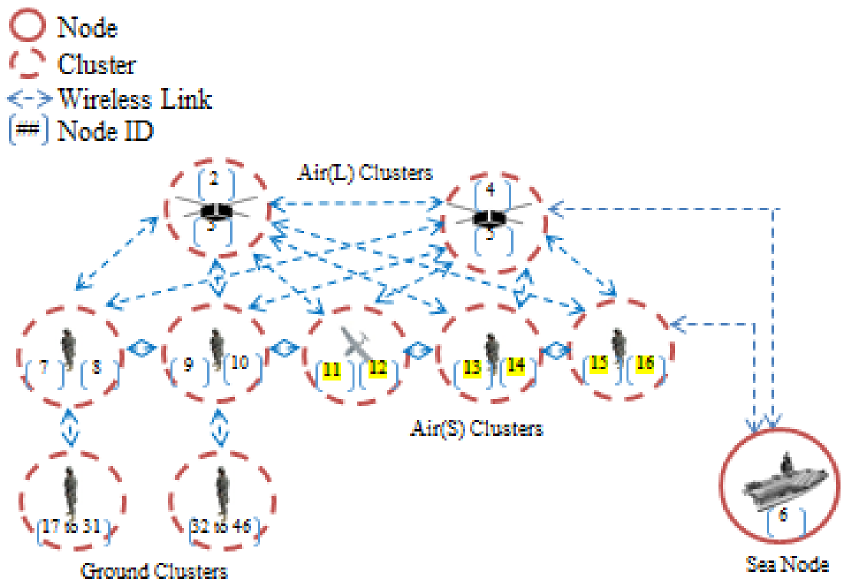

Figure 64. Operational Scenario IV. Adapted from [1].

The purpose of this scenario is to analyze the robustness of the simulation model after the implementation of an additional Air(L) cluster with network traffic generated by a separate ground cluster.

The nodes 11, 12, 13, 14, 15, and 16 are deactivated 10.0 s into the simulation to simulate the situation whereby these nodes have malfunctioned and the data and network traffic have to find alternative routes to reach the destination node. Network parameters like the average delay time, average jitter time, throughput, and packet loss are recorded.

The EXata software tool was used to verify the simulation model and determine the network parameters.

1. Simulation Result for Scenario IV

The simulation results generated by EXata were used to determine the routing of information in the simulation model using the parameters such as data bytes forwarded and received. The result up to Node 16 is shown in Figure 65.

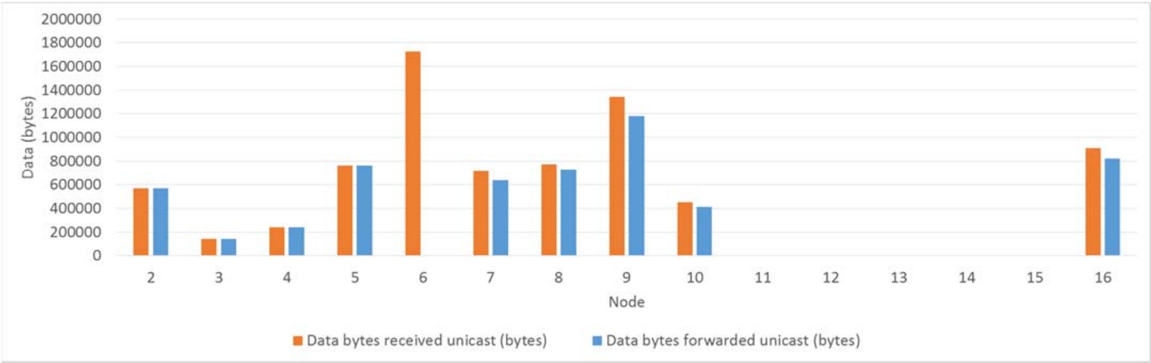

Figure 65. Data Bytes Forwarded and Received by Individual Nodes

The simulation results indicate that the main bulk of traffic follows a routing path through nodes 2, 3, 4, 5, 7, 8, 9, 10, and 16 before reaches the destination Node 6.

The simulation result for the average delay, unicast jitter and packet drop by individual node up to Node 46 are shown in Figures 66 to 68.

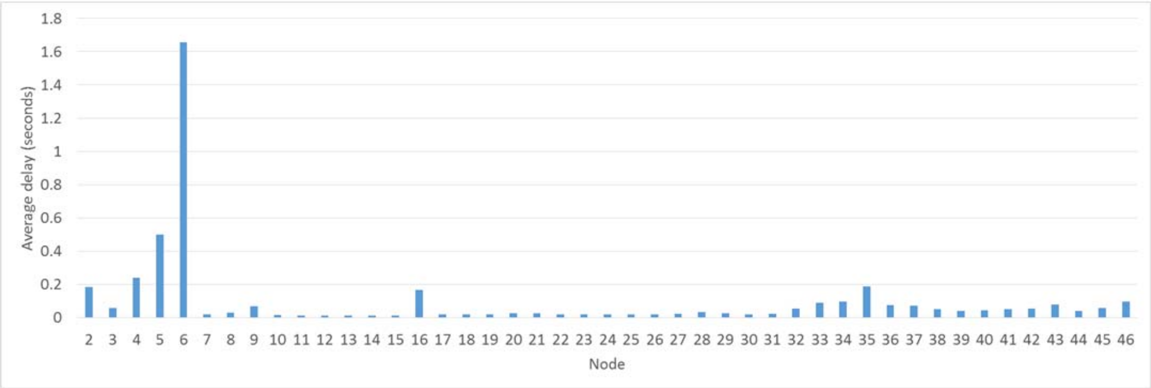

Figure 66. Average Delay Up to Node 46

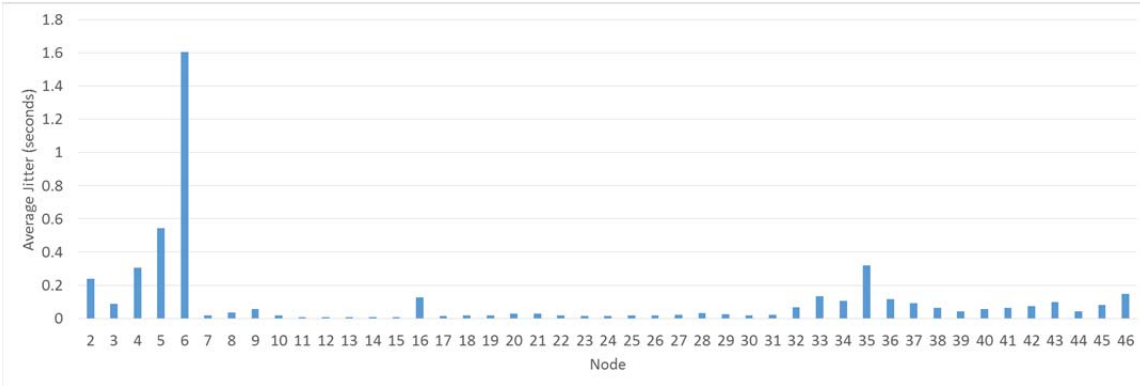

Figure 67. Average Jitter Up to Node 46

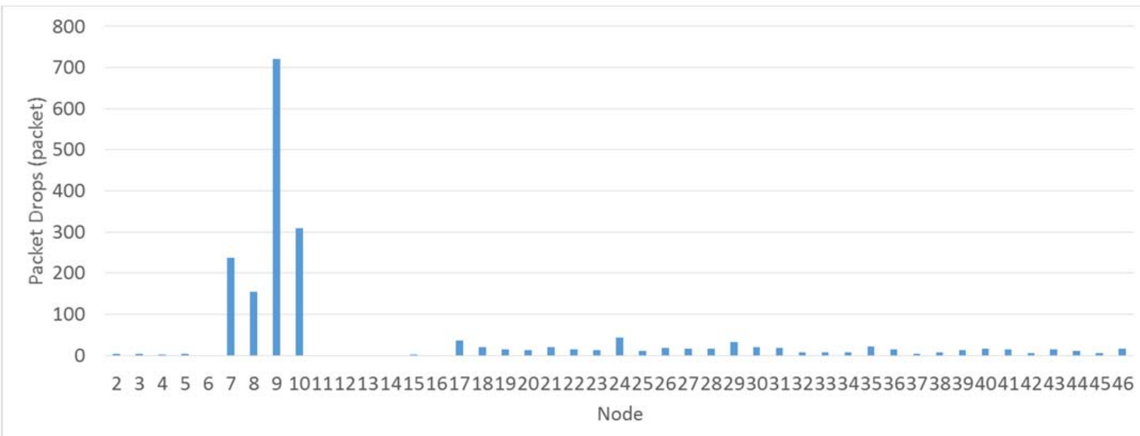

Figure 68. Packet Drop by Individual Nodes

The throughput results extracted from the destination Node 6 for source nodes 17 to 46 is shown in Figure 69. The 30 columns of throughput values correspond to the 15 source nodes generating data traffic and 15 source nodes generating network traffic using CBR generators.

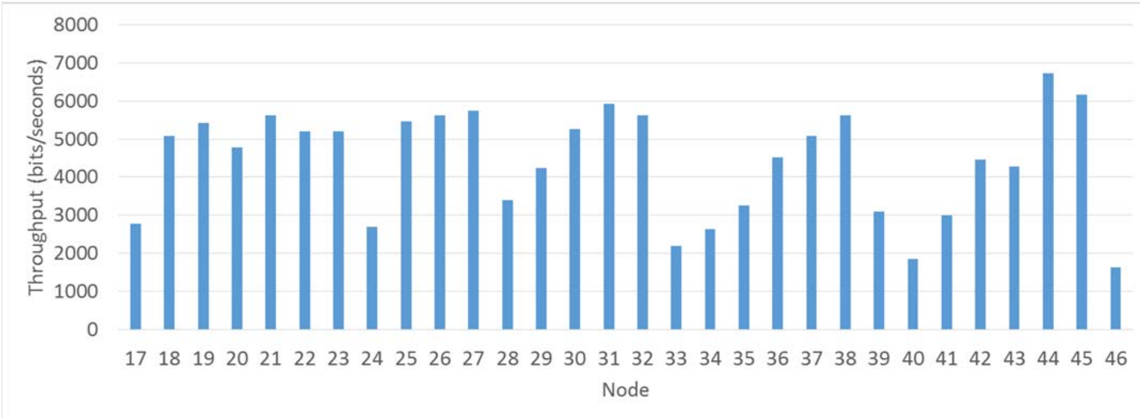

Figure 69. Throughput at Destination Node 6

The simulation result of the total packet drops up to Node 46 using the 1.0, 5.5, and 11.0 Mbps data rates is consolidated in Figure 70.

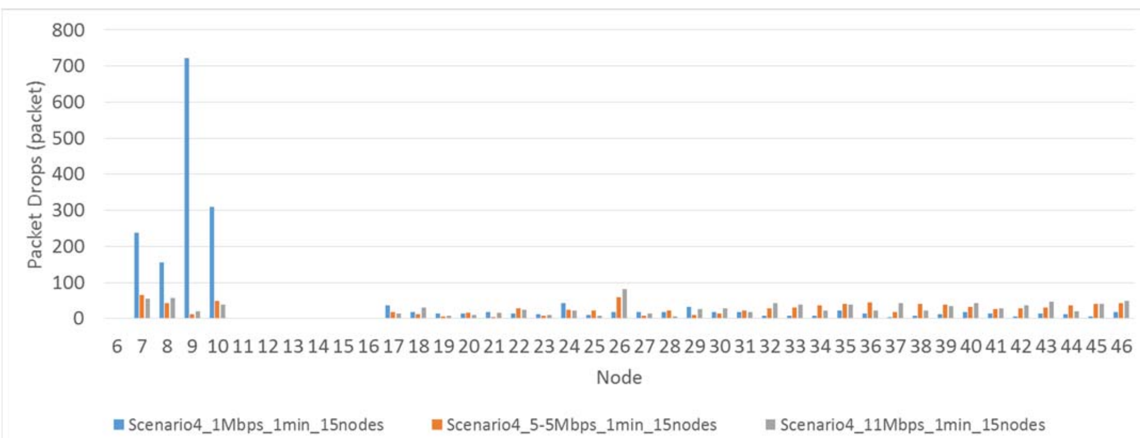

Figure 70. Total Packet Drops for Different Data Rates

We observe that the average end-to-end delay for each node generating CBR data traffic to the destination node increases up to 2.46 s in the presence of network traffic. This additional end-to-end delay time is caused by the network traffic which is generating data packets at shorter time intervals. Since more data packets enter and leave each intermediate node, the time for one data packet to arrive at the destination node is increased due to packet handling and queuing at each node. The effect of network traffic on the average end-to-end delay time for the 15 nodes simulating data traffic in scenario III and IV is shown in Figure 71.

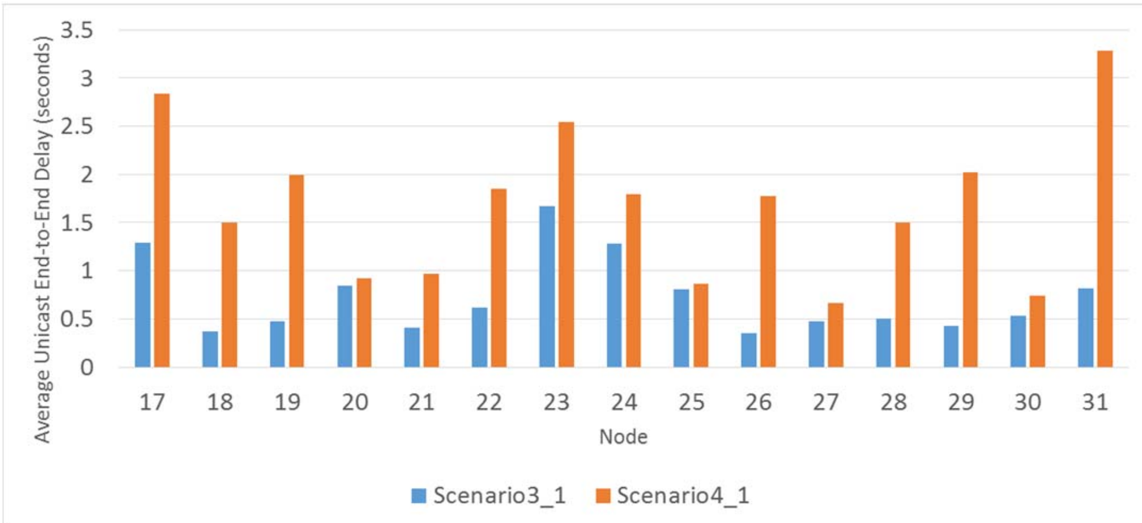

Figure 71. Average End-to-End Delay for Scenario III and IV

The average unicast jitter is increased up to 0.48 s for the scenario whereby network traffic is present. The data packets generated by the network traffic at shorter time intervals populate the channel before the data packets generated by data traffic arrive at the intermediate node; hence, the average unicast jitter, which is a time measurement of inter-arrival time of data packets, for the source node generating data traffic increases. This happens because these data packets take a longer time to arrive at the destination node due to traffic congestion in the channel. The effect of network traffic on the average jitter time for the 15 nodes simulating data traffic in scenario III and IV is shown in Figure 72.

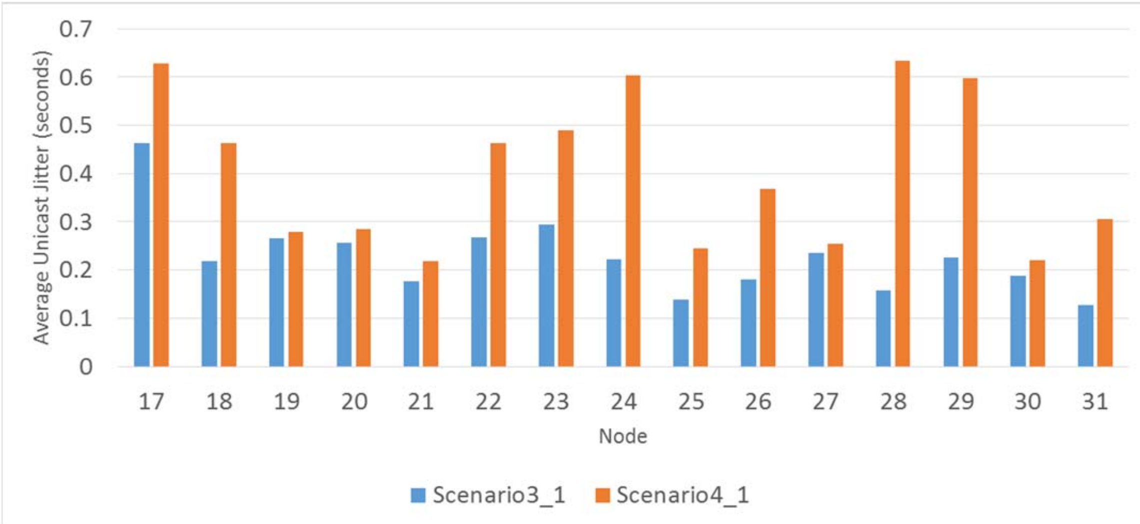

Figure 72. Average Jitter Time Comparison for Scenario III and IV

The unicast received throughput is reduced up to 5632 bits per second in the presence of network traffic. The reason for the decrease of throughput is due to traffic congestion in the channel, which causes the number of data packets arriving at the destination node to be reduced within the simulation time. The effect of network traffic on the throughput for the 15 nodes simulating data traffic in scenario III and IV is shown in Figure 73.

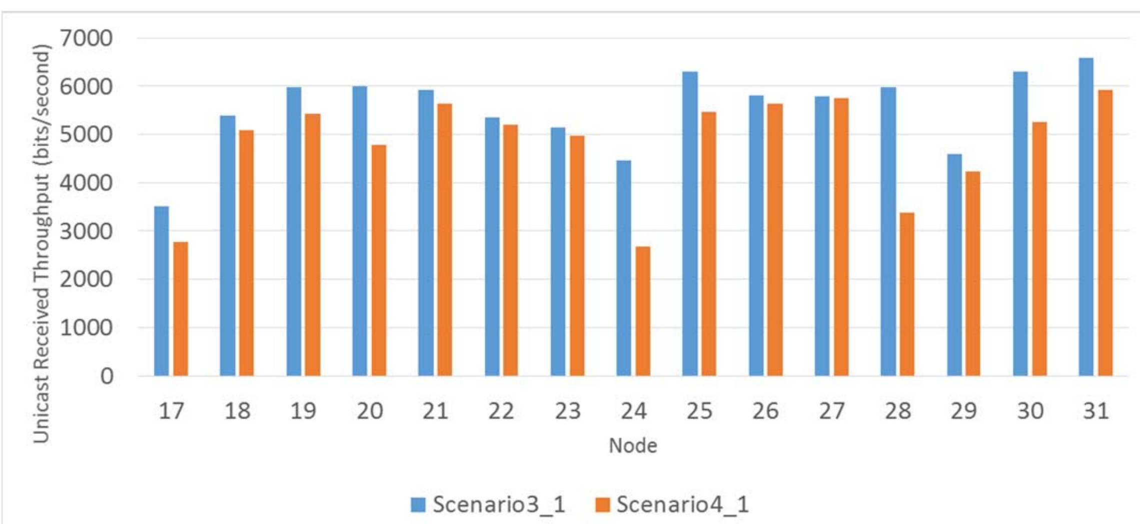

Figure 73. Throughput Comparison for Scenario III and IV

We observe that the average end-to-end delay and unicast jitter duration are higher than the simulation results obtained in scenario III. The higher end-to-end delay and unicast jitter values are caused by the 15 nodes in a ground cluster generating additional network traffic.

E. SCENARIO V: SIMPLIFIED FULL MODEL

In this operational scenario, a space node (e.g., CubeSat) is added to the simulation model to provide redundancy for the multi-tier network architecture. The space node relays information from an Air(L) cluster to a sea node. The visual representation for this scenario is shown in Figure 74. The data rate of 55.975 kbps is used for the wireless connection to CubeSat and 1.0 Mbps is used for the rest of the connection unless otherwise stated.

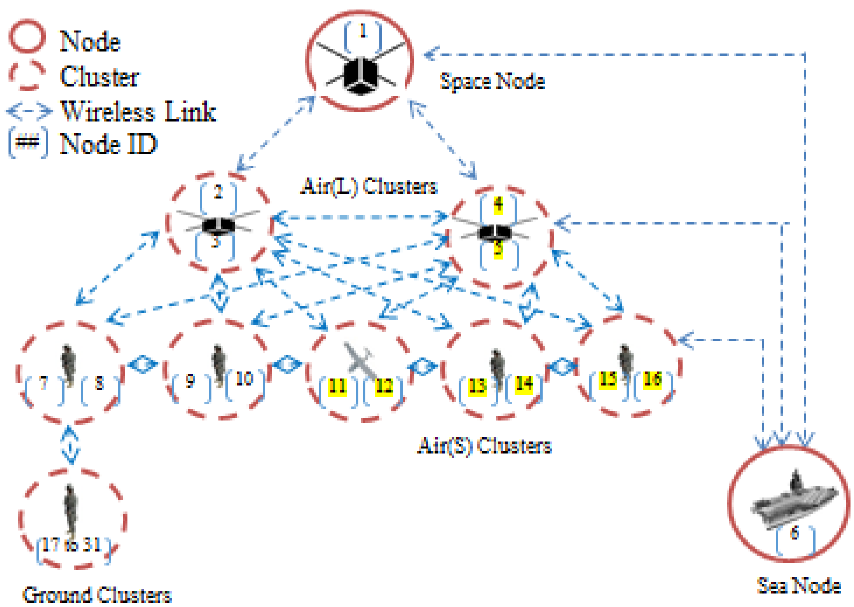

Figure 74. Operational Scenario V. Adapted from [1].

The purpose for this scenario is to analyze the robustness of the simulation model after the addition of a space node. The nodes 4, 5, 11, 12, 13, 14, 15, and 16 are deactivated 10.0 s into the simulation to simulate a situation whereby these nodes have malfunctioned and the data traffic have to find alternative routes to reach the destination node. Network parameters like the average delay time, average jitter time, throughput, and packet loss were recorded. The EXata software tool was used to verify the simulation model and determine the network parameters.

1. Simulation Result for Scenario V

The simulation results generated by EXata are used to determine the routing of information in the simulation model using parameters such as data bytes forwarded and received. The result up to Node 16 is shown in Figure 75.

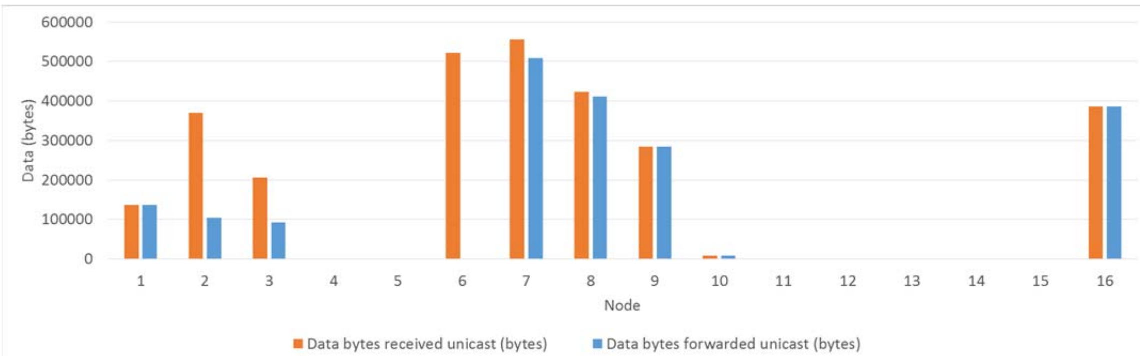

Figure 75. Data Bytes Forwarded and Received by Individual Nodes

The simulation results show that the data traffic generated by the CBR generator from the ground node to sea node follows a routing path through nodes 1, 2, 3, 7, 8, 9, 10, and 16 before reaches the destination Node 6.

Based on the simulation results, we observe that the data received at Node 6 are packets that are routed through Node 16 during the first 10.0 s and, thereafter, the data packets are rerouted through nodes 1, 2, and 3 after nodes 4, 5, 11, 12, 13, 14, 15, and 16 are deactivated.

The simulation result for the average delay, unicast jitter and total packet drops up to Node 31 are shown in Figures 76 to 78.

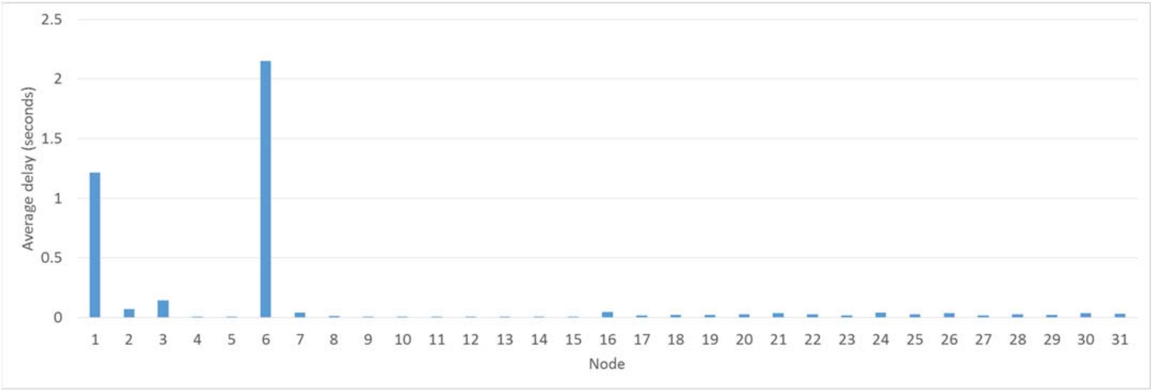

Figure 76. Average Delay Up to Node 31

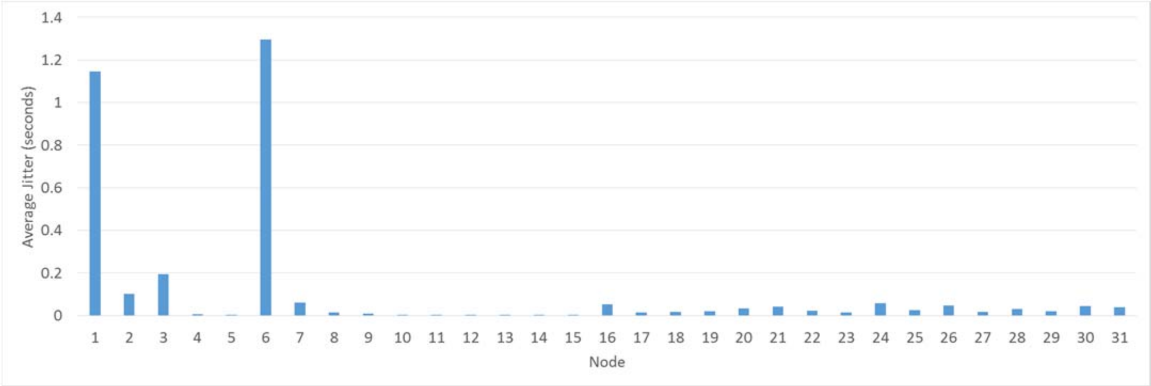

Figure 77. Average Jitter Up to Node 31

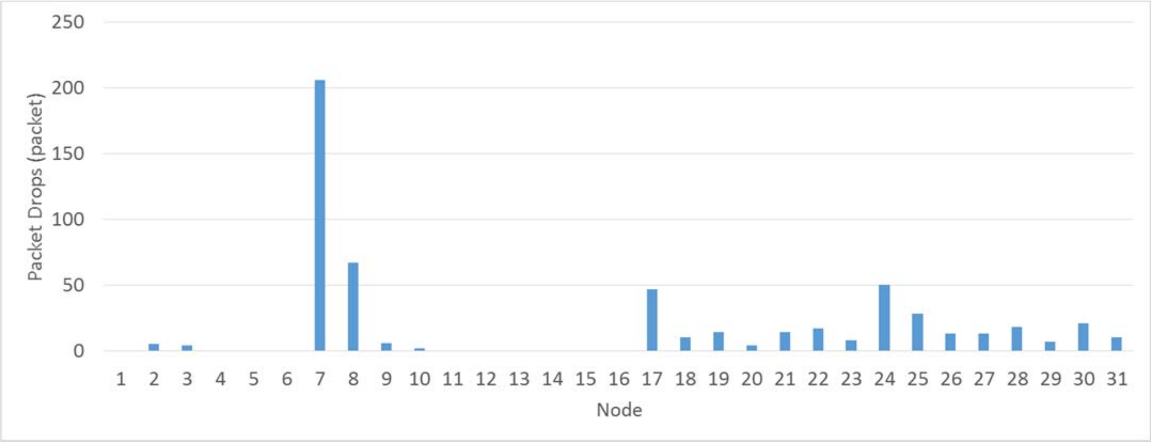

Figure 78. Total Packet Drops Up to Node 31

The throughput results extracted from the simulation result at destination Node 6 for source nodes 17 to 31 is shown in Figure 79. The 15 columns of throughput values correspond to the 15 source nodes simulating data traffic using CBR generators.

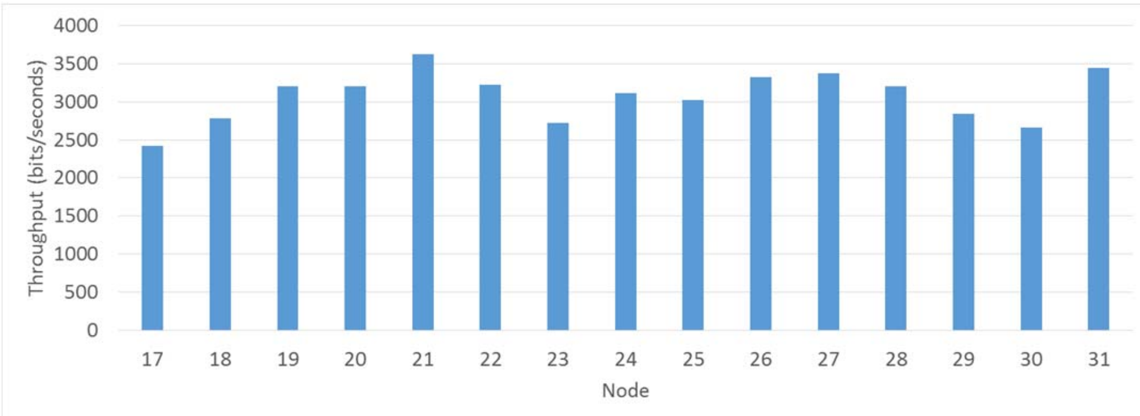

Figure 79. Throughput at Destination Node 6

The simulation result of the total packet drop up to Node 31 using the 1.0, 5.5, and 11.0 Mbps data rates is consolidated in Figure 80.

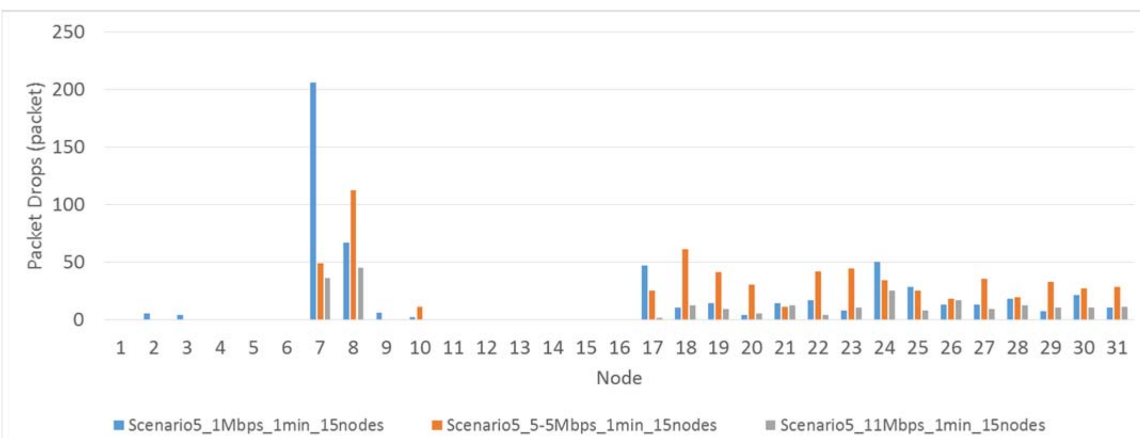

Figure 80. Total Packet Drops for Different Data Rate

F. SCENARIO VI: SIMPLIFIED FULL MODEL WITH NETWORK TRAFFIC

In this operational scenario, the ground cluster relays information to the sea node through the air clusters and space nodes in the presence of simulated network traffic generated by a separate ground cluster. The visual representation for this scenario is shown in Figure 81. The data rate of 55.975 kbps is used for the wireless connection to CubeSat and 1.0 Mbps is used for the rest of the connection unless otherwise stated.

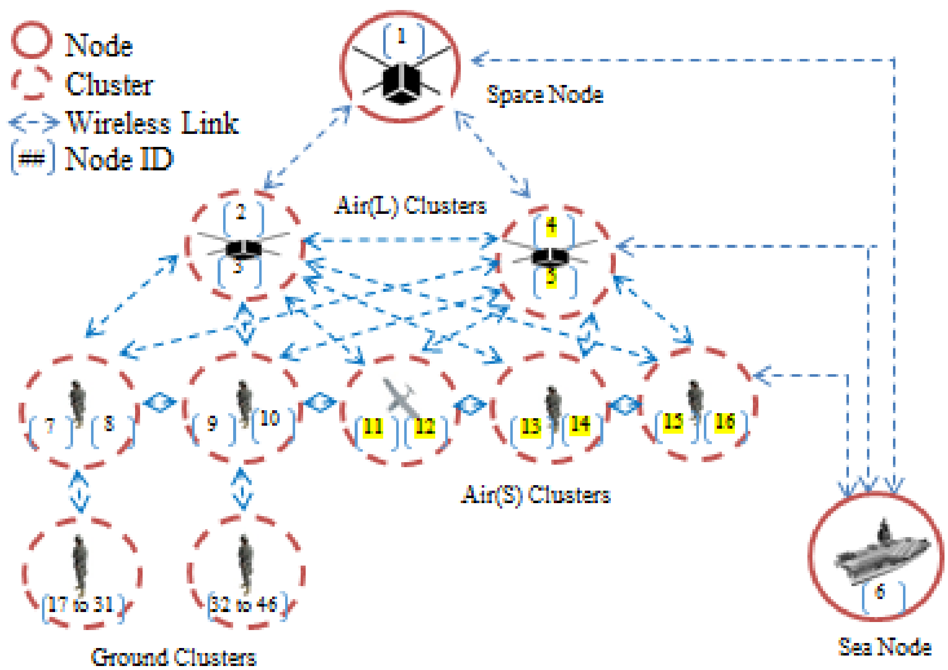

Figure 81. Operational Scenario VI. Adapted from [1].

The purpose of this scenario is to analyze the robustness of the simulation model after the implementation of a space node with network traffic generated by a separate ground cluster.

The nodes 4, 5, 11, 12, 13, 14, 15, and 16 are deactivated 10.0 s into the simulation to simulate the situation whereby these nodes have malfunctioned and the data and network traffic have to have alternative routes to reach the destination Node 6. Network parameters like the average delay time, average jitter time, throughput, and packet loss are recorded. The EXata software tool was used to verify the simulation model and determine the network parameters.

1. Simulation Result for Scenario VI

The simulation results generated by EXata were used to determine the routing of information in the simulation model using the parameters such as data bytes forwarded and received. The result up to Node 16 is shown in Figure 82.

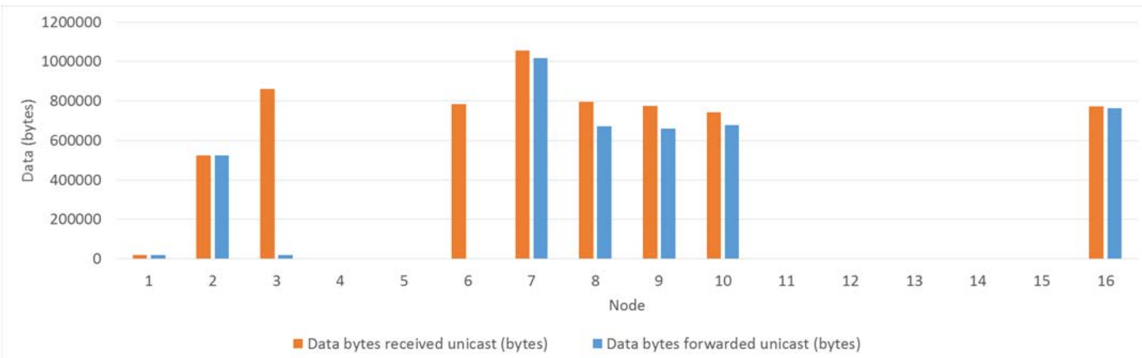

Figure 82. Data Bytes Forwarded and Received by Individual Nodes

The simulation results indicate that the main bulk of traffic follows a routing path through nodes 1, 2, 3, 7, 8, 9, 10, and 16 before reaches the destination Node 6.

Based on the simulation results, we observe that there are data packets routing through the air clusters and reaching the destination node before any nodes have been deactivated in the first 10.0 s of the simulation.

The simulation results for the average delay, average jitter and total packet drop time up to Node 46 are shown in Figures 83 to 85.

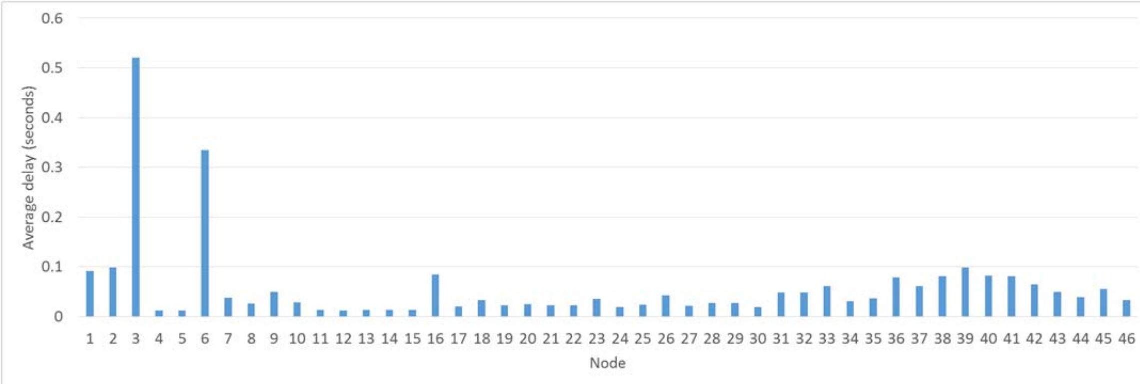

Figure 83. Average Delay Up to Node 46

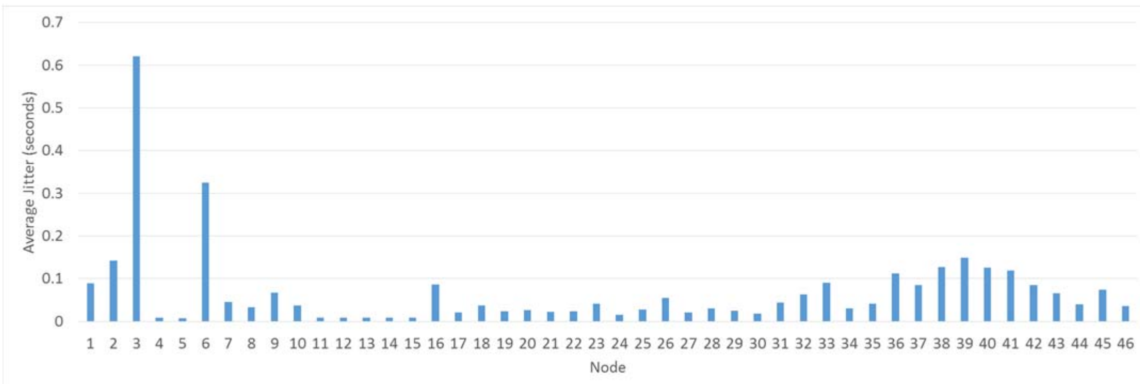

Figure 84. Average Jitter Up to Node 46

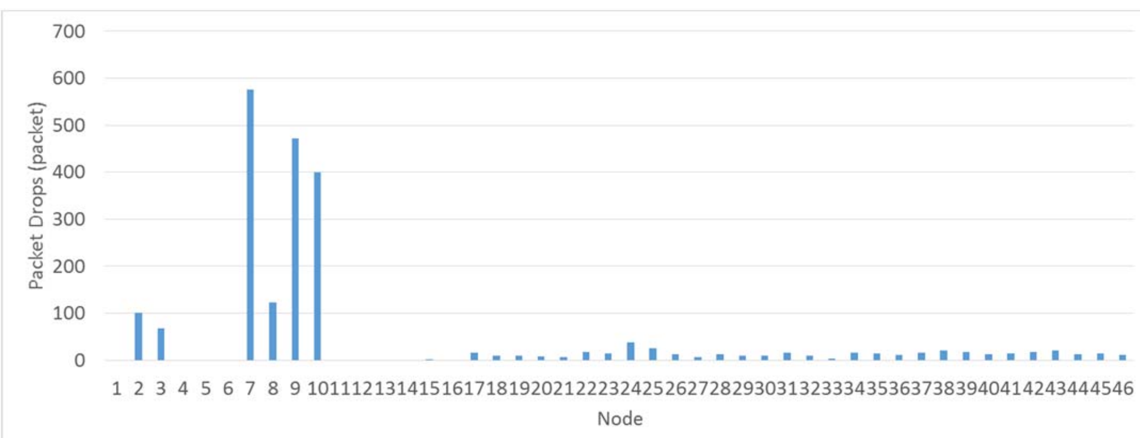

Figure 85. Total Packet Drops Up to Node 46

The throughput results extracted from the destination Node 6 for source nodes 17 to 46 is shown in Figure 86. The 30 columns of throughput values correspond to the 15 source nodes generating data traffic and 15 source nodes generating network traffic using CBR generators.

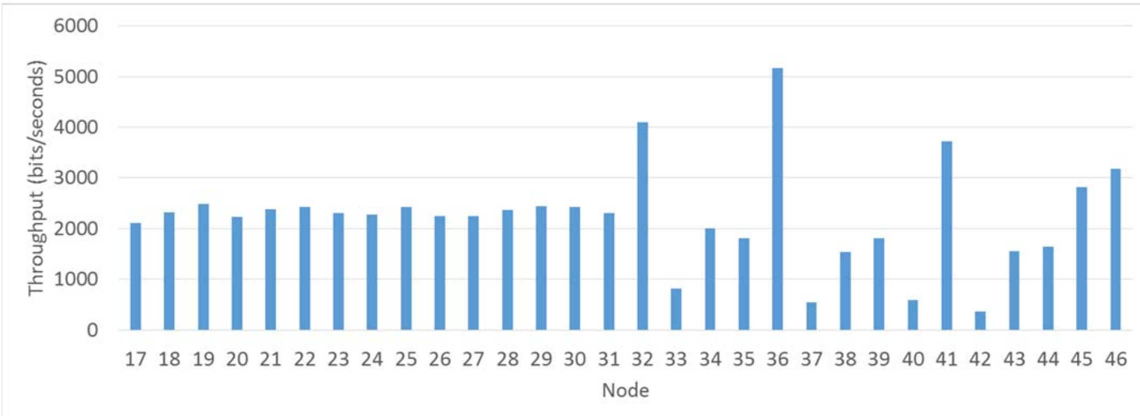

Figure 86. Throughput at Destination Node 6

The simulation result of the total packet drop up to Node 46 using the 1.0, 5.5, and 11.0 Mbps data rates is consolidated in Figure 87. The packet drop for scenario VI is exceptionally high at the Air(S) nodes that are wirelessly connected to the Air(L) nodes.

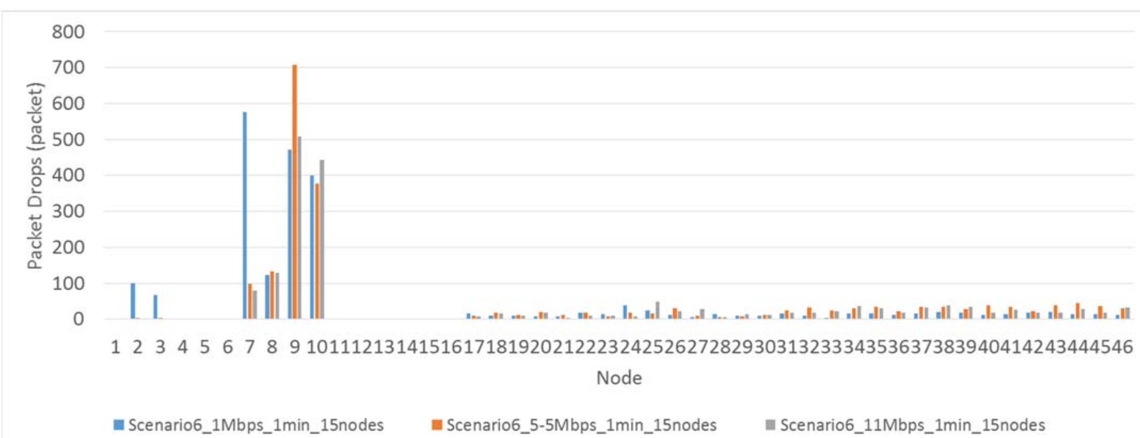

Figure 87. Total Packet Drop for Different Data Rate

The effect of network traffic on the average end-to-end delay time for the 15 nodes simulating data traffic in scenario V and VI is shown in Figure 88.

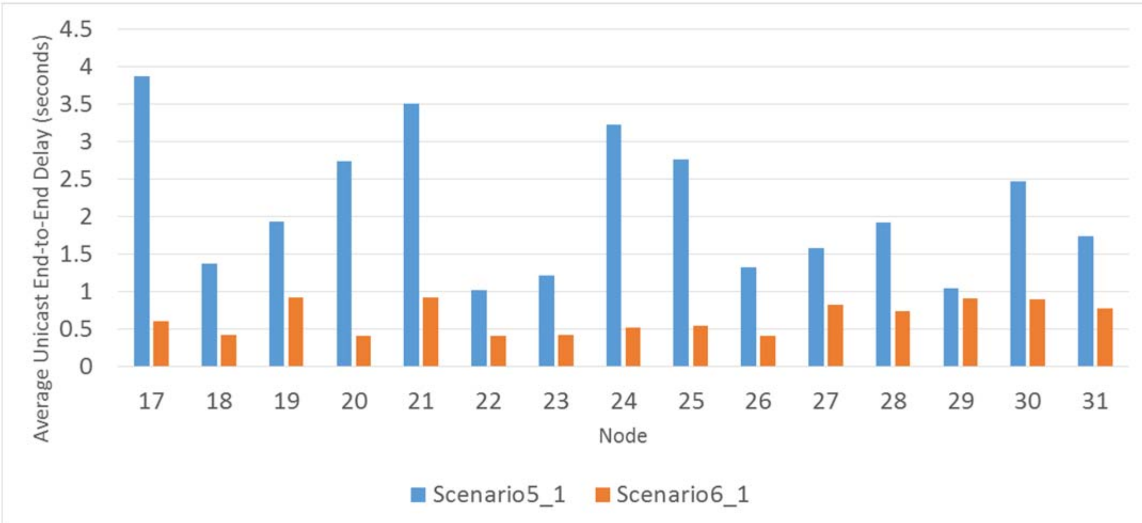

Figure 88. Average End-to-End Delay Time Comparison for Scenarios V and VI

The average unicast jitter comparison between scenario V and VI is shown in Figure 89.

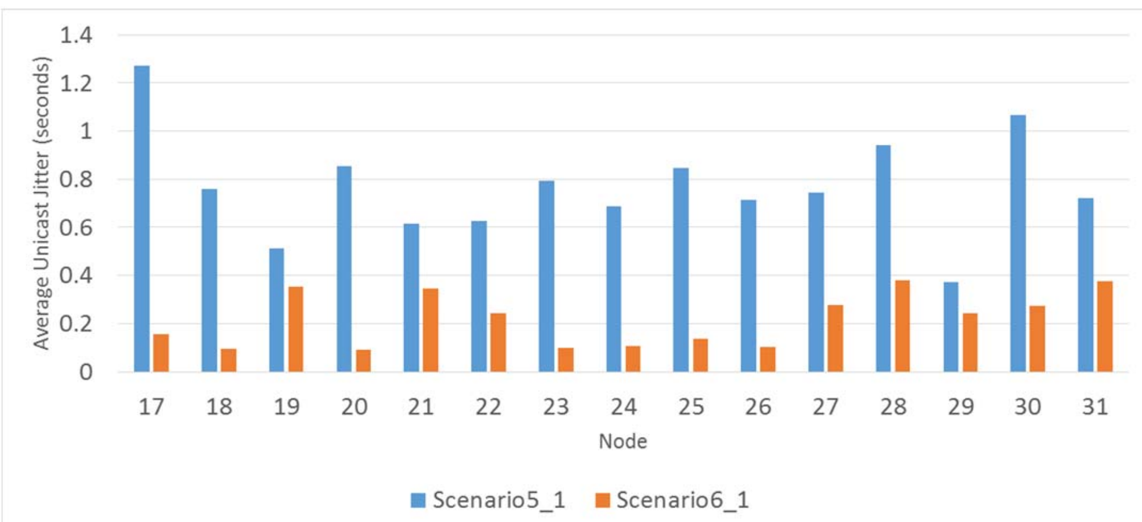

Figure 89. Average Jitter Time Comparison for Scenarios V and VI

The way that the EXata software determines the average end-to-end delay, unicast jitter and unicast received throughput is based on the data packets that reach the destination node within the simulation period.

We spotted an anomaly for the simulation output for scenario VI since the network performance in the presence of network traffic produces a lower average end-to-end delay, lower unicast jitter and higher unicast received throughput, which is not consistent with the earlier scenarios II and IV.

Further investigation into the generated statistic file reveals that all the time stamped for the last data packet received at destination Node 6 are under 10.0 s. This observation can be traced back to the simulation model whereby nodes are de-activated 10.0 s into the simulation to simulate the situation of node or cluster malfunction. The observation indicates that the data packet originating from the data traffic is able to reach the destination node through Air(S) nodes during the first 10.0 s into the simulation. Thereafter, the data packets are not able to reach the destination Node 6. The reason for the data packet not reaching the destination node is either it is in transit through the only CubeSat route or has been dropped after exceeding the retransmission limit; hence, the result generated by the EXata software may not truly represent the network performance.

In order to correctly represent the scenario and determine the network performance, the node or cluster malfunction is activated at the start of the simulation. The revised scenario (labelled as Scenario6_1Z) does not cause incorrect interpretations of the result since the data packets are not routed through the Air(S) nodes to reach the destination node. The result obtained from the revised scenario only contains the simulation result through the CubeSat route.

Based on the simulation results for the revised scenario, we observe a consistent trend when comparing with scenarios II and IV. The lower throughput for scenario VI indicates a higher packet drop due to network congestion. As highlighted previously, the increase in data rate does not improve the throughput since the energy per bit and SNR per bit decreases. This, in turn, causes an increase in bit error probability that causes more errors at the receiver, resulting in more packet drops and lower throughput.

The simulation results for average end-to-end delay, unicast jitter and throughput for this scenario are shown in Figures 90 to 92.

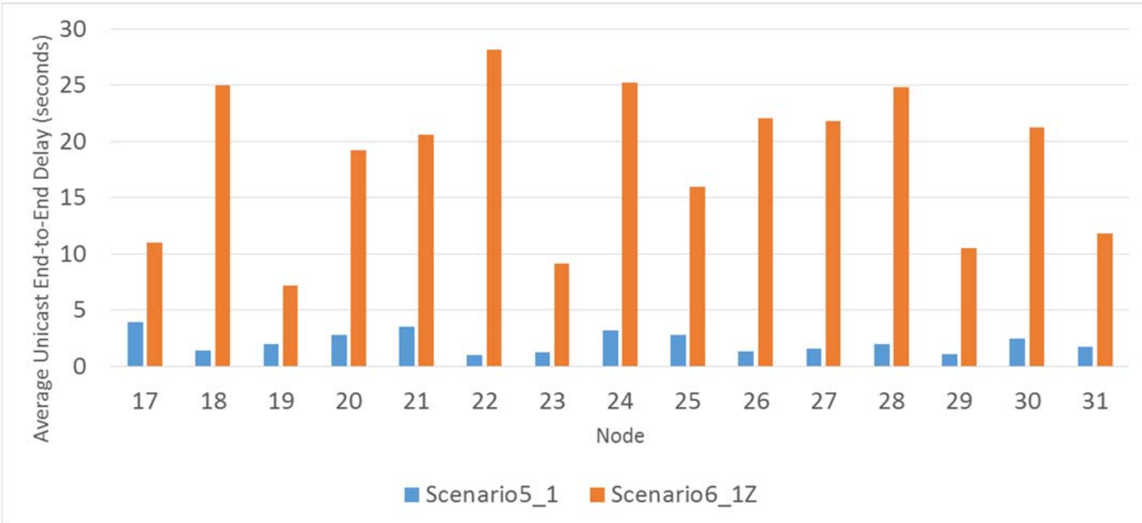

Figure 90. Average End-to-End Delay Comparison for Revised Scenarios V and VI

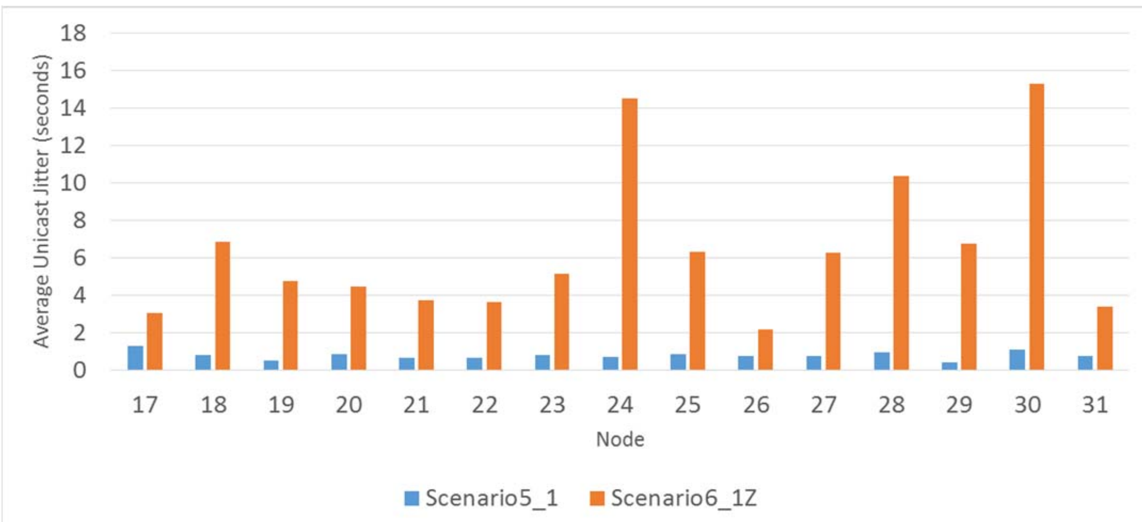

Figure 91. Average Unicast Jitter Comparison for Revised Scenarios V and VI

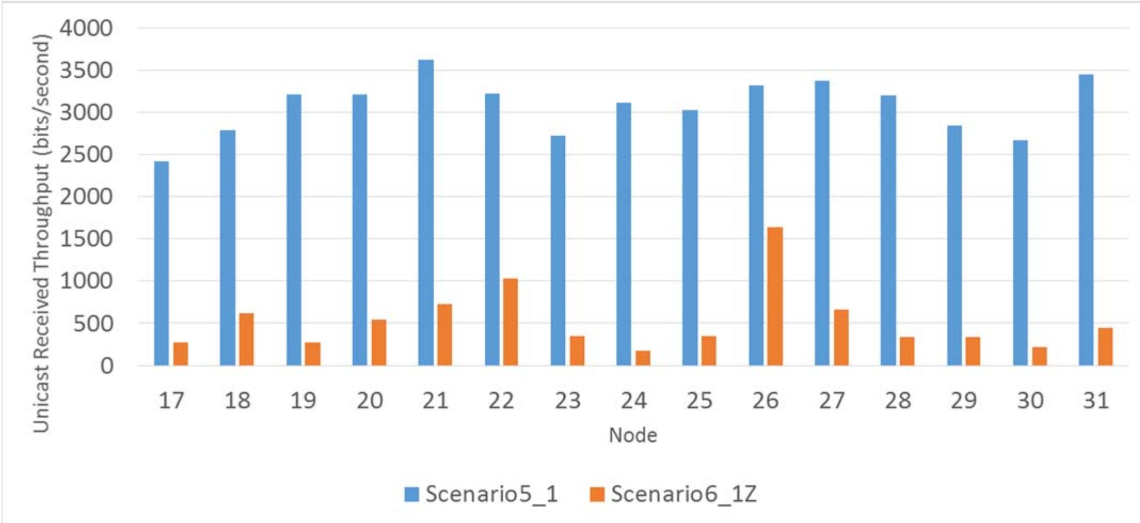

Figure 92. Throughput Comparison for Revised Scenarios V and VI

Based on the simulation results for all the operational scenarios, we conclude that the simulation model representing the multi-tier network architecture is able to search for alternative routes in the event of deactivated nodes or clusters based on IEEE 802.11b MAC and DYMO routing protocol with the enable processing hello option checked.

Focusing on scenario II, IV, and VI, we observe that the network traffic simulated by a separate ground cluster using CBR generator increases the average end-to-end delay, increases the average unicast jitter duration, and decreases the throughput for the data traffic that are originating from the source to the destination Node 6.

Based on the simulation results from scenario V and VI, we recommend not to use a CubeSat as a relaying node unless necessary due to the low throughput. In fact, the multi-tier network architecture collapsed due to a timeout situation where data packets could not reach the destination node in the given (simulation) time.

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VI. CONCLUSION AND FUTURE WORK

The communication nodes, connectivity options, and schemes available for a proposed multi-tier communication network are defined in this thesis.

A concept of operations for the multi-tier network was proposed, a link budget analysis and software simulation to validate the model were performed, and multiple scenarios in the EXata software tool to determine network performance were created. In these scenarios, we compared the performance under degraded environments whereby some nodes are deactivated during the simulation. The results indicate that redundancy in the simulation model enables information to be redistributed through an alternative route to the destination node. Channel availability is also improved due to fewer occurrences of network bottleneck and congestion.

In addition, the simulation model also indicates that relaying data packets through a space (CubeSat) node produces incorrect network parameters since the traffic data packets are unable to reach the destination node within the simulation time. The CubeSat can be used to send critical data that requires low bit rates.

For future work, other communication methods, such as free-space optics (FSO) and long-term evolution (LTE) communications, can be evaluated to determine whether their performance is significantly better than the proposed radio frequency (RF) multi-tier communication network. Also, the concerns of high-altitude clouds in the Earth’s atmosphere affecting FSO communications and the advantage of LTE versus RF for better data security pose an opportunity for more in-depth research.

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APPENDIX A. LINK BUDGET ANALYSIS

Link budget analysis for data rates of 1.0, 2.0, 5.5, and 54.0 Mbps for the multi-tier network architecture are consolidated in Tables 15 to 22. The link budget analysis using the SNR per bit of 9.0, 12.0, 15.0, and 18.0 dB is consolidated in Tables 23 to 52.

Table 15. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 1.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−21.7	−21.8	−15.2	−7.8	−7.7	−15.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−131.9	−131.9	−131.9	−131.9	−131.9	−131.9
Bit Rate (dBbps)	60.0	60.0	60.0	60.0	60.0	60.0
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 16. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 1.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	1.0	1.1	−6.1	−6.2	1.1	1.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−144.5	−144.5	−131.9	−131.9	−144.5	−144.5
Bit Rate (dBbps)	47.5	47.5	60.0	60.0	47.5	47.5
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 17. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 2.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−18.7	−18.8	−12.2	−4.8	−4.7	−12.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−128.9	−128.9	−128.9	−128.9	−128.9	−128.9
Bit Rate (dBbps)	63.0	63.0	63.0	63.0	63.0	63.0
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 18. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 2.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	1.0	1.1	−3.1	−3.1	1.1	1.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−144.5	−144.5	−128.9	−128.9	−144.5	−144.5
Bit Rate (dBbps)	47.5	47.5	63.0	63.0	47.5	47.5
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 19. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 5.5 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−14.3	−14.4	−7.8	−0.4	−0.3	−7.8
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−124.5	−124.5	−124.5	−124.5	−124.5	−124.5
Bit Rate (dBbps)	67.4	67.4	67.4	67.4	67.4	67.4
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 20. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 5.5 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	1.0	1.1	1.3	1.2	1.1	1.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−144.5	−144.5	−124.5	−124.5	−144.5	−144.5
Bit Rate (dBbps)	47.5	47.5	67.4	67.4	47.5	47.5
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 21. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 54.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−4.3	−4.5	2.1	9.5	9.6	2.1
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−114.6	−114.6	−114.6	−114.6	−114.6	−114.6
Bit Rate (dBbps)	77.3	77.3	77.3	77.3	77.3	77.3
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER 10^{-5} (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER 10^{-6} (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 22. Link Budget Analysis (E_b/N_o = 9.0 dB, R = 54.0 Mbps) for Link #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	1.0	1.1	11.3	11.2	1.1	1.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−144.5	−144.5	−114.6	−114.6	−144.5	−144.5
Bit Rate (dBbps)	47.5	47.5	77.3	77.3	47.5	47.5
Energy Per Bit (dBJ)	−191.9	−191.9	−191.9	−191.9	−191.9	−191.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	9.0	9.0	9.0	9.0	9.0	9.0
Required Eb/No for QPSK BER $10^{–4}$ (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER $10^{–5}$ (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER $10^{–6}$ (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER $10^{–4}$ (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER $10^{–5}$ (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER $10^{–6}$ (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER $10^{–4}$ (dB)	1.7	1.7	1.7	1.7	1.7	1.7
Link Margin for QPSK BER $10^{–5}$ (dB)	1.5	1.5	1.5	1.5	1.5	1.5
Link Margin for QPSK BER $10^{–6}$ (dB)	1.5	1.5	1.5	1.5	1.5	1.5

Table 23. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 1.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−18.7	−18.8	−12.2	−4.8	−4.7	−12.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−128.9	−128.9	−128.9	−128.9	−128.9	−128.9
Bit Rate (dBbps)	60.0	60.0	60.0	60.0	60.0	60.0
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 24. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 1.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	4.0	4.1	-3.1	–3.2	4.1	4.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	–141.5	–141.5	–128.9	–128.9	–141.5	–141.5
Bit Rate (dBbps)	47.5	47.5	60.0	60.0	47.5	47.5
Energy Per Bit (dBJ)	–188.9	–188.9	–188.9	–188.9	–188.9	–188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 25. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 2.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−15.7	−15.8	−9.2	−1.8	−1.7	−9.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−125.9	−125.9	−125.9	−125.9	−125.9	−125.9
Bit Rate (dBbps)	63.0	63.0	63.0	63.0	63.0	63.0
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 26. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 2.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	4.0	4.1	−0.1	−0.1	4.1	4.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−141.5	−141.5	−125.9	−125.9	−141.5	−141.5
Bit Rate (dBbps)	47.5	47.5	63.0	63.0	47.5	47.5
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 27. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 5.5 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	–11.3	–11.4	–4.8	2.6	2.7	–4.8
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	–121.5	–121.5	–121.5	–121.5	–121.5	–121.5
Bit Rate (dBbps)	67.4	67.4	67.4	67.4	67.4	67.4
Energy Per Bit (dBJ)	–188.9	–188.9	–188.9	–188.9	–188.9	–188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 28. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 5.5 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	4.0	4.1	4.3	4.2	4.1	4.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−141.5	−141.5	−121.5	−121.5	−141.5	−141.5
Bit Rate (dBbps)	47.5	47.5	67.4	67.4	47.5	47.5
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 29. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 11.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−8.3	−8.4	−1.8	5.6	5.7	−1.8
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−118.5	−118.5	−118.5	−118.5	−118.5	−118.5
Bit Rate (dBbps)	70.4	70.4	70.4	70.4	70.4	70.4
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 30. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 11.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	4.0	4.1	7.3	7.3	4.1	4.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−141.5	−141.5	−118.5	−118.5	−141.5	−141.5
Bit Rate (dBbps)	47.5	47.5	70.4	70.4	47.5	47.5
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 31. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 54.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−1.3	−1.5	5.1	12.5	12.6	5.1
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−111.6	−111.6	−111.6	−111.6	−111.6	−111.6
Bit Rate (dBbps)	77.3	77.3	77.3	77.3	77.3	77.3
Energy Per Bit (dBJ)	−188.9	−188.9	−188.9	−188.9	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	12.0	12.0	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	4.7	4.7	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	4.5	4.5	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	4.5	4.5	4.5	4.5

Table 32. Link Budget Analysis (E_b/N_o = 12.0 dB, R = 54.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	4.0	4.1	13.0	13.0	4.1	4.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−141.5	−141.5	−112.9	−112.8	−141.5	−141.5
Bit Rate (dBbps)	47.5	47.5	77.3	77.3	47.5	47.5
Energy Per Bit (dBJ)	−188.9	−188.9	−190.2	−190.1	−188.9	−188.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	12.0	12.0	10.7	10.8	12.0	12.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	4.7	4.7	3.4	3.5	4.7	4.7
Link Margin for QPSK BER 10^{-5} (dB)	4.5	4.5	3.2	3.3	4.5	4.5
Link Margin for QPSK BER 10^{-6} (dB)	4.5	4.5	3.2	3.3	4.5	4.5

Table 33. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 1.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−15.7	−15.8	−9.2	−1.8	−1.7	−.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−125.9	−125.9	−125.9	−125.9	−125.9	−125.9
Bit Rate (dBbps)	60.0	60.0	60.0	60.0	60.0	60.0
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−185.9	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 34. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 1.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	7.0	7.1	–0.1	-0.2	7.1	7.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	–138.5	–138.5	–125.9	–125.9	–138.5	–138.5
Bit Rate (dBbps)	47.5	47.5	60.0	60.0	47.5	47.5
Energy Per Bit (dBJ)	–185.9	–185.9	–185.9	–185.9	–185.9	–185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 35. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 2.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−12.7	−12.8	−6.2	1.2	1.3	−6.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−122.9	−122.9	−122.9	−122.9	−122.9	−122.9
Bit Rate (dBbps)	63.0	63.0	63.0	63.0	63.0	63.0
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−185.9	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 36. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 2.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	7.0	7.1	2.9	2.9	7.1	7.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−138.5	−138.5	−122.9	−122.9	−138.5	−138.5
Bit Rate (dBbps)	47.5	47.5	63.0	63.0	47.5	47.5
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−185.9	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 37. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 5.5 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	–8.3	–8.4	–1.8	5.6	5.7	–1.8
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	–118.5	–118.5	–118.5	–118.5	–118.5	–118.5
Bit Rate (dBbps)	67.4	67.4	67.4	67.4	67.4	67.4
Energy Per Bit (dBJ)	–185.9	–185.9	–185.9	–185.9	–185.9	–185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 38. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 5.5 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	7.0	7.1	7.3	7.2	7.1	7.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−138.5	−138.5	−118.5	−118.5	−138.5	−138.5
Bit Rate (dBbps)	47.5	47.5	67.4	67.4	47.5	47.5
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−185.9	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 39. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 11.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−5.3	−5.4	1.2	8.6	8.7	1.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−115.5	−115.5	−115.5	−115.5	−115.5	−115.5
Bit Rate (dBbps)	70.4	70.4	70.4	70.4	70.4	70.4
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−185.9	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	7.5	7.5	7.5

Table 40. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 11.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	7.0	7.1	10.3	10.3	7.1	7.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−138.5	−138.5	−115.5	−115.5	−138.5	−138.5
Bit Rate (dBbps)	47.5	47.5	70.4	70.4	47.5	47.5
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−185.9	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	15.0	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	7.7	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	7.5	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	8.4	8.4	8.4	8.4	8.4	8.4

Table 41. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 54.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	1.7	1.5	8.1	13.0	13.0	8.1
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−108.6	−108.6	−108.6	−111.1	−111.2	−108.6
Bit Rate (dBbps)	77.3	77.3	77.3	77.3	77.3	77.3
Energy Per Bit (dBJ)	−185.9	−185.9	−185.9	−188.4	−188.5	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	15.0	12.5	12.4	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	7.7	5.2	5.1	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	7.5	5.0	4.9	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	7.5	5.0	4.9	7.5

Table 42. Link Budget Analysis (E_b/N_o = 15.0 dB, R = 54.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	7.0	7.1	13.0	13.0	7.1	7.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−138.5	−138.5	−112.9	−112.8	−138.5	−138.5
Bit Rate (dBbps)	47.5	47.5	77.3	77.3	47.5	47.5
Energy Per Bit (dBJ)	−185.9	−185.9	−190.2	−190.1	−185.9	−185.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	15.0	15.0	10.7	10.8	15.0	15.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	7.7	7.7	3.4	3.5	7.7	7.7
Link Margin for QPSK BER 10^{-5} (dB)	7.5	7.5	3.2	3.3	7.5	7.5
Link Margin for QPSK BER 10^{-6} (dB)	7.5	7.5	3.2	3.3	7.5	7.5

Table 43. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 1.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−12.7	−12.8	−6.2	1.2	1.3	−6.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−122.9	−122.9	−122.9	−122.9	−122.9	−122.9
Bit Rate (dBbps)	60.0	60.0	60.0	60.0	60.0	60.0
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−182.9	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 44. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 1.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	10.0	10.1	2.9	2.8	10.1	10.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−135.5	−135.5	−122.9	−122.9	−135.5	−135.5
Bit Rate (dBbps)	47.5	47.5	60.0	60.0	47.5	47.5
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−182.9	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 45. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 2.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−9.7	−9.8	−3.2	4.2	4.3	−3.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−119.9	−119.9	−119.9	−119.9	−119.9	−119.9
Bit Rate (dBbps)	63.0	63.0	63.0	63.0	63.0	63.0
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−182.9	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 46. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 2.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	10.0	10.1	5.9	5.9	10.1	10.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−135.5	−135.5	−119.9	−119.9	−135.5	−135.5
Bit Rate (dBbps)	47.5	47.5	63.0	63.0	47.5	47.5
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−182.9	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 47. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 5.5 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	−5.3	−5.4	1.2	8.6	8.7	1.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−115.5	−115.5	−115.5	−115.5	−115.5	−115.5
Bit Rate (dBbps)	67.4	67.4	67.4	67.4	67.4	67.4
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−182.9	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 48. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 5.5 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	10.0	10.1	10.3	10.2	10.1	10.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−135.5	−135.5	−115.5	−115.5	−135.5	−135.5
Bit Rate (dBbps)	47.5	47.5	67.4	67.4	47.5	47.5
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−182.9	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 49. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 11.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	–2.3	–2.4	4.2	11.6	11.7	4.2
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	–112.5	–112.5	–112.5	–112.5	–112.5	–112.5
Bit Rate (dBbps)	70.4	70.4	70.4	70.4	70.4	70.4
Energy Per Bit (dBJ)	–182.9	–182.9	–182.9	–182.9	–182.9	–182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	–200.9	–200.9	–200.9	–200.9	–200.9	–200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	18.0	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	10.7	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5

Table 50. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 11.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	10.0	10.1	13.0	13.0	10.1	10.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−135.5	−135.5	−112.9	−112.8	−135.5	−135.5
Bit Rate (dBbps)	47.5	47.5	70.4	70.4	47.5	47.5
Energy Per Bit (dBJ)	−182.9	−182.9	−183.3	−183.2	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	17.7	17.7	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.4	10.4	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.2	10.2	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.2	10.2	10.5	10.5

Table 51. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 54.0 Mbps) for Links #1–6

Link	**1**	**2**	**3**	**4**	**5**	**6**
Signal	Ground-Air(S)	Air(S)-Ship	Air(S)-Air(S)	Air(S)-Air(L)	Air(L)-Air(S)	Air(L)-Air(L)
Power Transmitted (dBW)	4.7	4.5	11.1	13.0	13.0	11.1
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Free-Space Path Loss (dB)	100.3	100.1	106.7	114.1	114.2	106.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	2.0	2.0	2.0	2.0	2.0	2.0
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−105.6	−105.6	−105.6	−111.1	−111.2	−105.6
Bit Rate (dBbps)	77.3	77.3	77.3	77.3	77.3	77.3
Energy Per Bit (dBJ)	−182.9	−182.9	−182.9	−188.4	−188.5	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	18.0	12.5	12.4	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	10.7	5.2	5.1	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	10.5	5.0	4.9	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	5.0	4.9	10.5

Table 52. Link Budget Analysis (E_b/N_o = 18.0 dB, R = 54.0 Mbps) for Links #7–12

Link	**7**	**8**	**9**	**10**	**11**	**12**
Signal	Air(L)-Space	Space-Air(L)	Ship-Air(L)	Air(L)-Ship	Ship-Space	Space-Ship
Power Transmitted (dBW)	10.0	10.1	13.0	13.0	10.1	10.0
Transmitter Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Transmitter Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Free-Space Path Loss (dB)	134.7	134.8	115.9	115.8	134.8	134.7
Miscellaneous Loss (dB)	10.0	10.0	10.0	10.0	10.0	10.0
Receiver Antenna Gain (dBi)	1.6	1.6	2.0	2.0	1.6	1.6
Receiver Cable Loss (dB)	2.0	2.0	2.0	2.0	2.0	2.0
Power Received (dBW)	−135.5	−135.5	−112.9	−112.8	−135.5	−135.5
Bit Rate (dBbps)	47.5	47.5	77.3	77.3	47.5	47.5
Energy Per Bit (dBJ)	−182.9	−182.9	−190.2	−190.1	−182.9	−182.9
Equivalent System Noise Temperature (dBK)	27.7	27.7	27.7	27.7	27.7	27.7
Noise Spectral Density (dBW/Hz)	−200.9	−200.9	−200.9	−200.9	−200.9	−200.9
Calculated Eb/No (dB)	18.0	18.0	10.7	10.8	18.0	18.0
Required Eb/No for QPSK BER 10^{-4} (dB)	8.3	8.3	8.3	8.3	8.3	8.3
Required Eb/No for QPSK BER 10^{-5} (dB)	9.5	9.5	9.5	9.5	9.5	9.5
Required Eb/No for QPSK BER 10^{-6} (dB)	10.5	10.5	10.5	10.5	10.5	10.5
Link Provision (dB)	3.0	3.0	3.0	3.0	3.0	3.0
Coding Gain for QPSK BER 10^{-4} (dB)	4.0	4.0	4.0	4.0	4.0	4.0
Coding Gain for QPSK BER 10^{-5} (dB)	5.0	5.0	5.0	5.0	5.0	5.0
Coding Gain for QPSK BER 10^{-6} (dB)	6.0	6.0	6.0	6.0	6.0	6.0
Link Margin for QPSK BER 10^{-4} (dB)	10.7	10.7	3.4	3.5	10.7	10.7
Link Margin for QPSK BER 10^{-5} (dB)	10.5	10.5	3.2	3.3	10.5	10.5
Link Margin for QPSK BER 10^{-6} (dB)	10.5	10.5	3.2	3.3	10.5	10.5

APPENDIX B. EXata SIMULATION RESULTS

The EXata simulation results up to Node 31 for the data rates of 5.5, and 11.0 Mbps representing the multi-tier network architecture are consolidated in Figures 93 to 114.

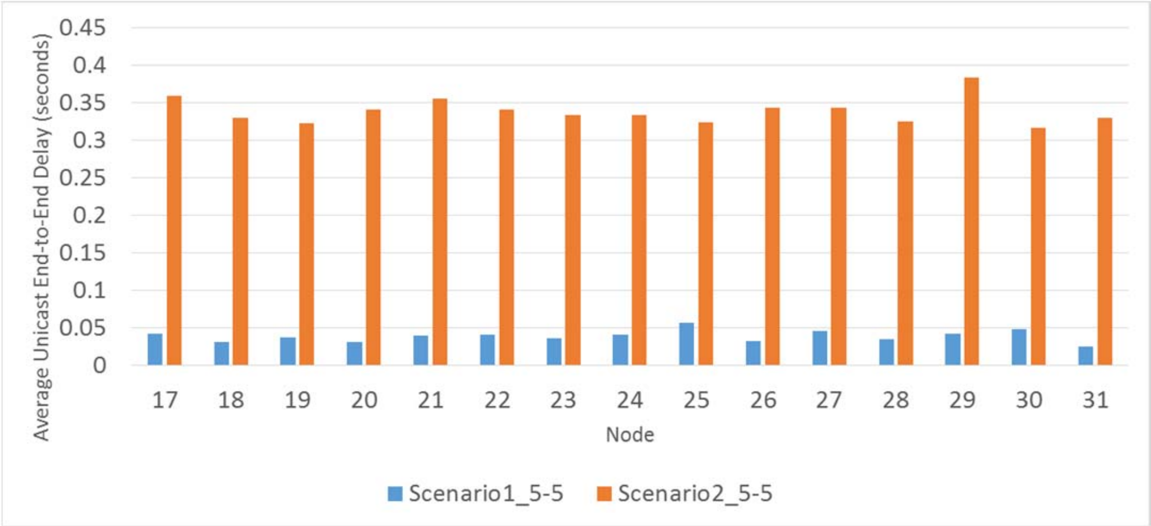

Figure 93. Average End-to-End Delay for 5.5-Mbps Data Rate in Scenarios I and II

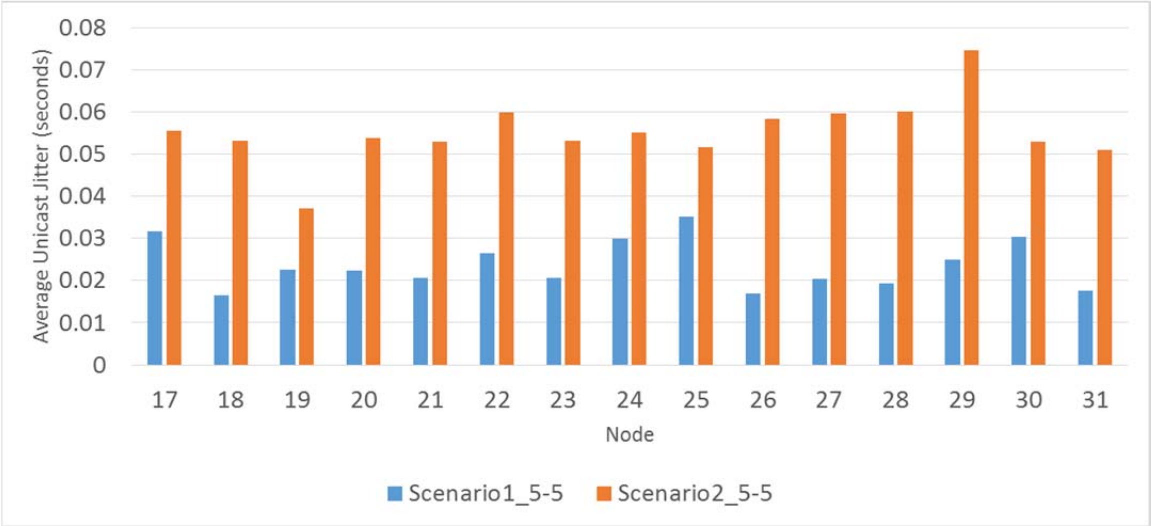

Figure 94. Average Jitter for 5.5-Mbps Data Rate in Scenarios I and II

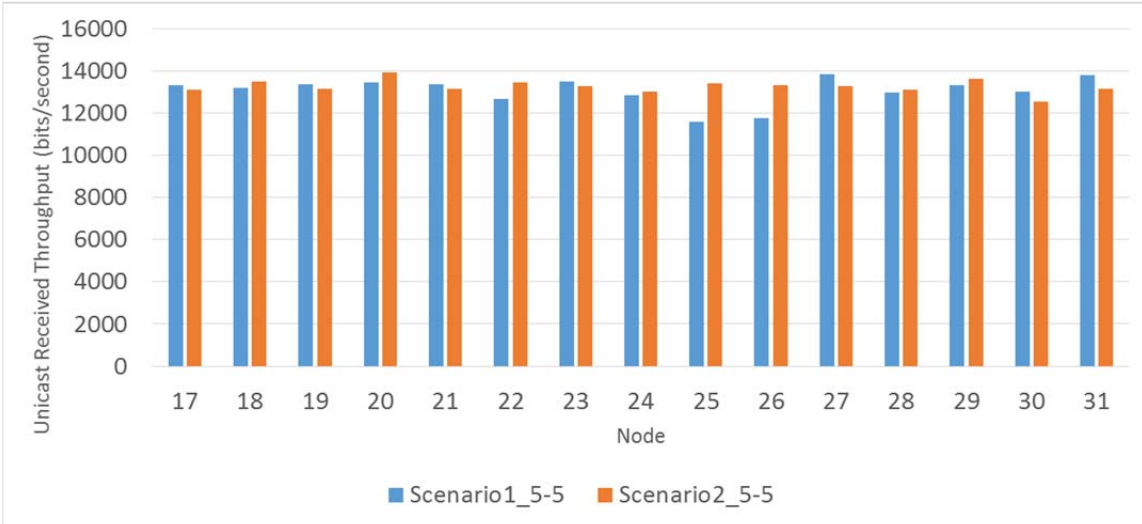

Figure 95. Throughput for 5.5-Mbps Data Rate in Scenarios I and II

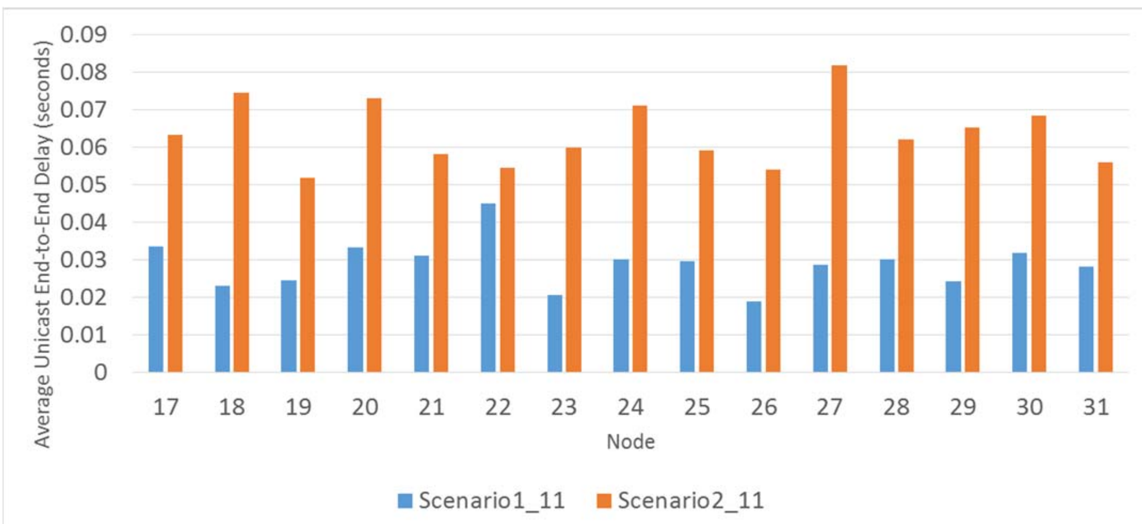

Figure 96. Average End-to-End Delay for 11.0-Mbps Data Rate in Scenarios I and II

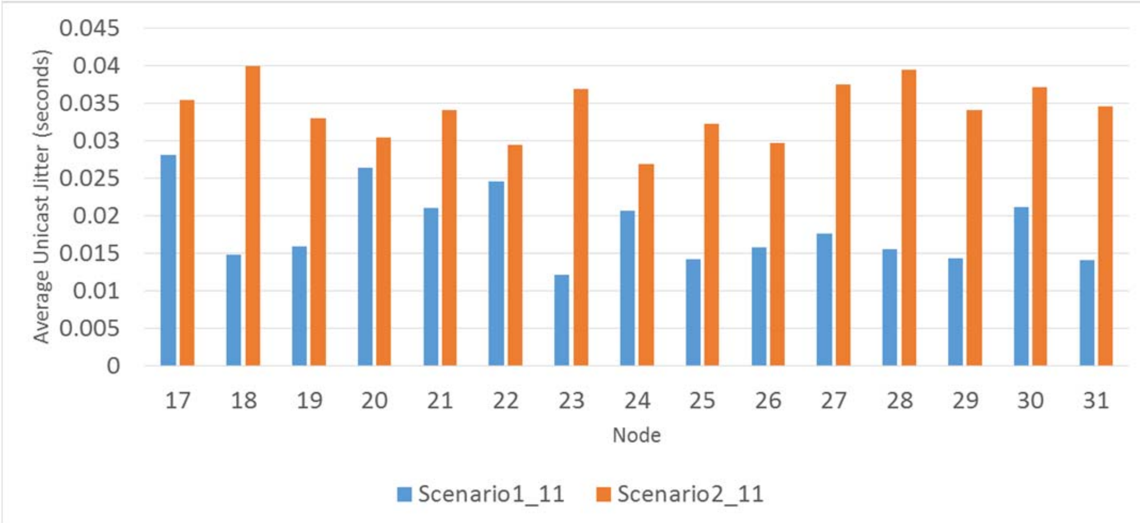

Figure 97. Average Jitter for 11.0-Mbps Data Rate in Scenarios I and II

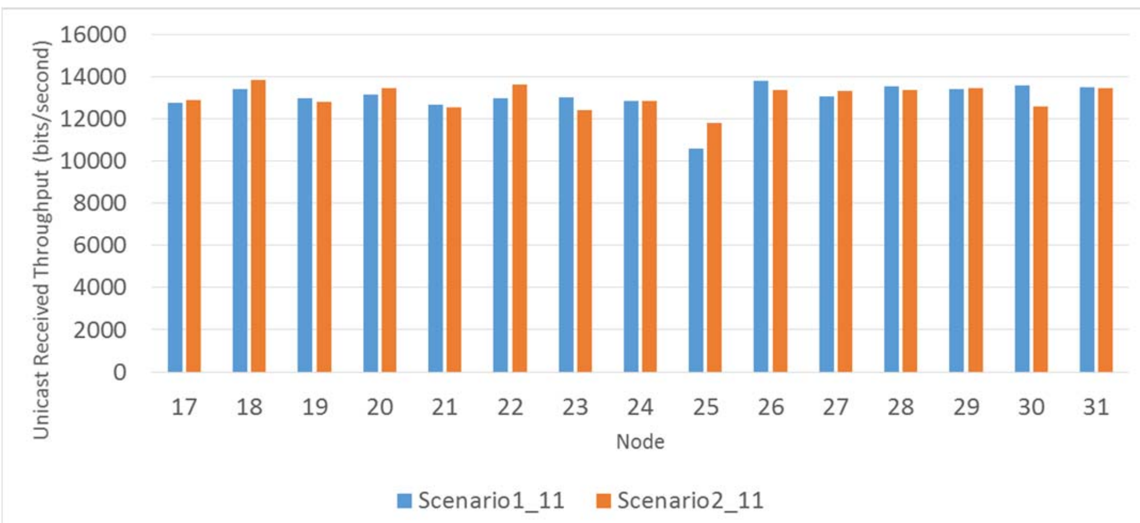

Figure 98. Throughput for 11.0-Mbps Data Rate in Scenarios I and II

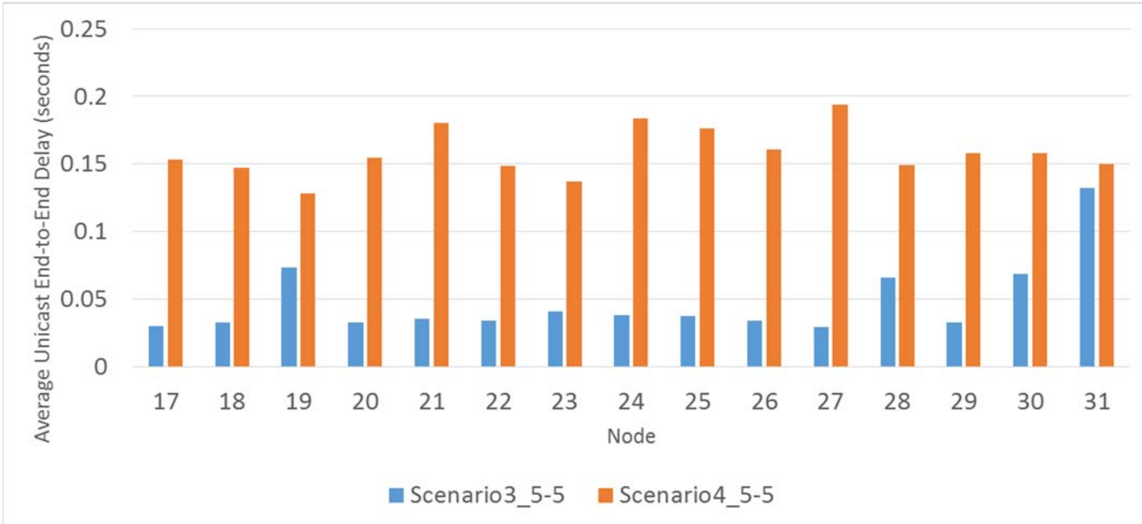

Figure 99. Average End-to-End Delay for 5.5-Mbps Data Rate in Scenarios III and IV

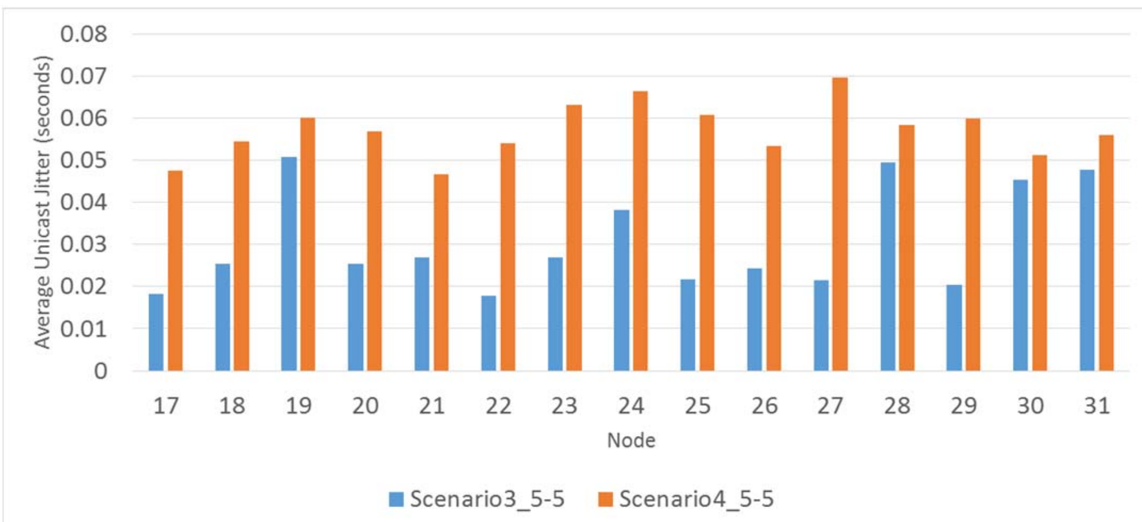

Figure 100. Average Jitter for 5.5-Mbps Data Rate in Scenarios III and IV

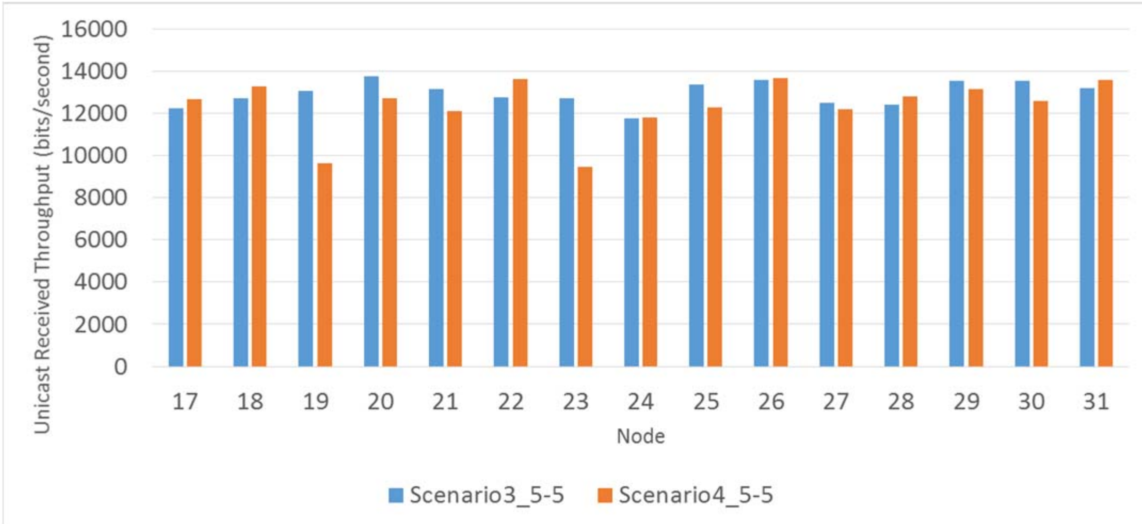

Figure 101. Throughput for 5.5-Mbps Data Rate in Scenarios III and VI

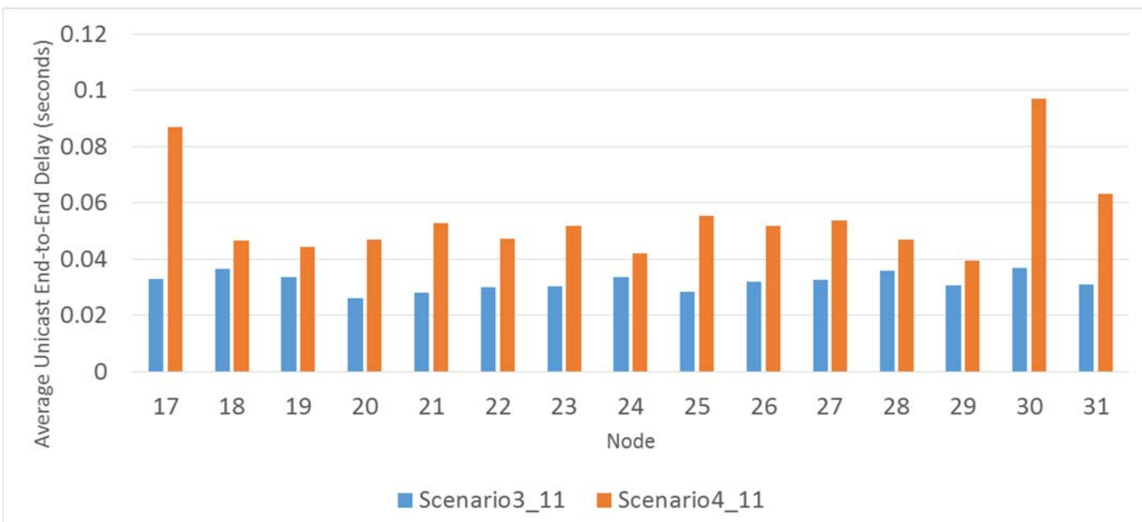

Figure 102. Average End-to-End Delay for 11.0-Mbps Data Rate in Scenarios III and IV

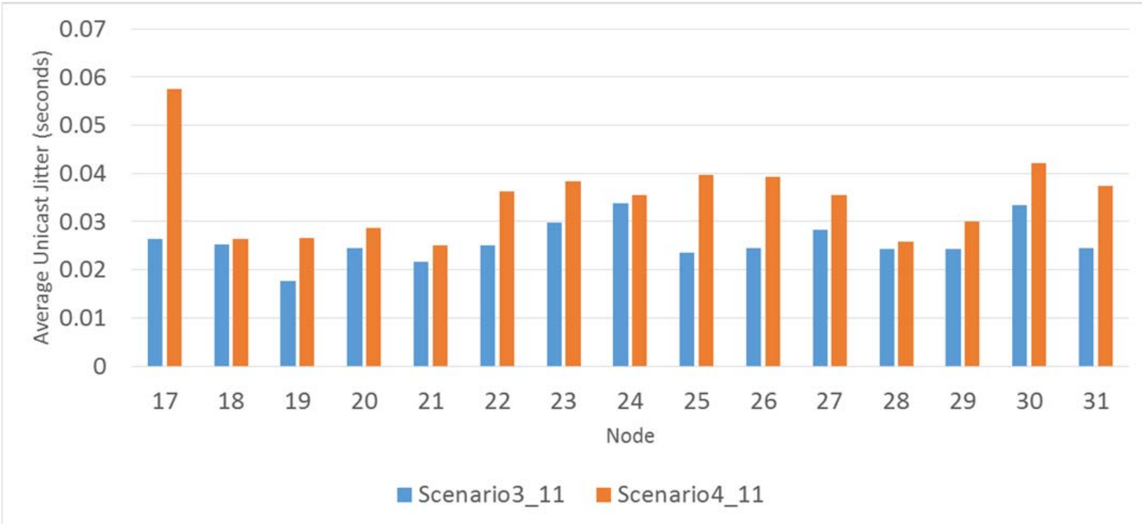

Figure 103. Average Jitter 11.0-Mbps Data Rate in Scenarios III and IV

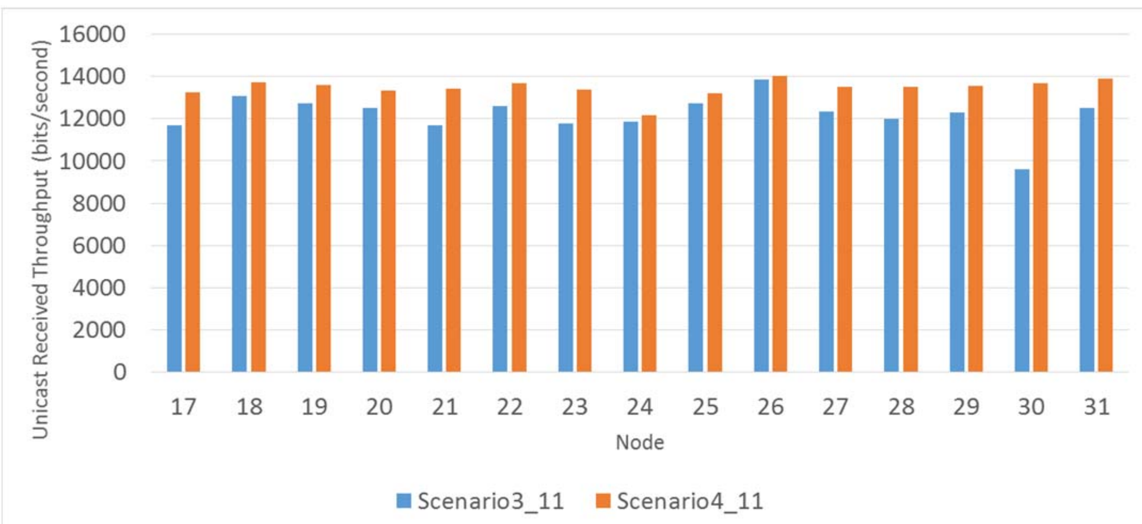

Figure 104. Throughput for 11.0-Mbps Data Rate in Scenarios III and VI

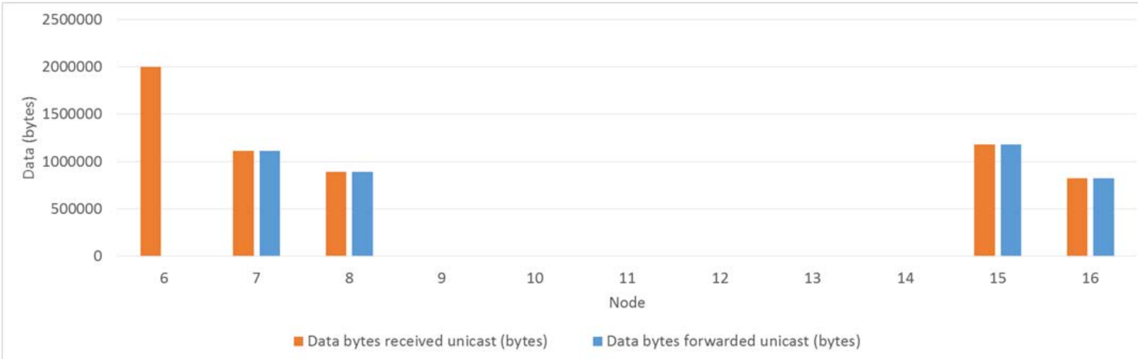

Figure 105. Data Forwarded and Received for 5.5-Mbps Data Rate in Scenario I

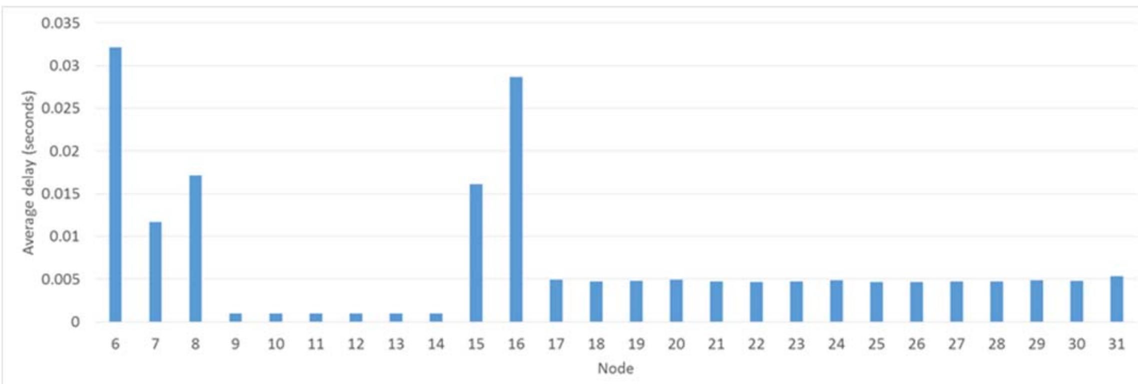

Figure 106. Average Delay for 5.5-Mbps Data Rate in Scenario I

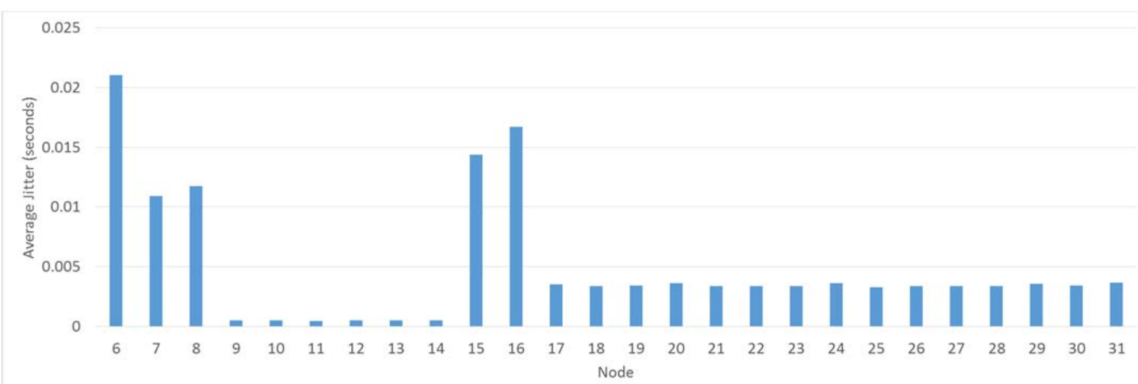

Figure 107. Average Jitter for 5.5-Mbps Data Rate in Scenario I

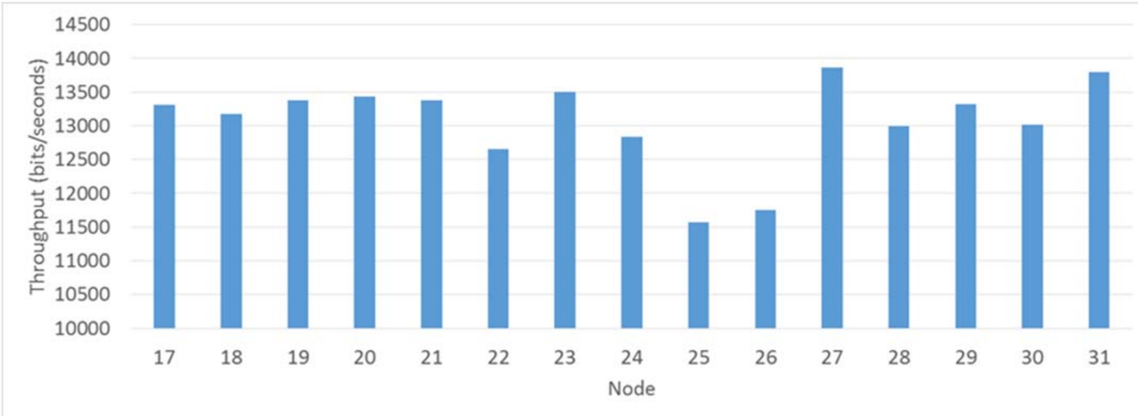

Figure 108. Throughput for 5.5-Mbps Data Rate in Scenario I

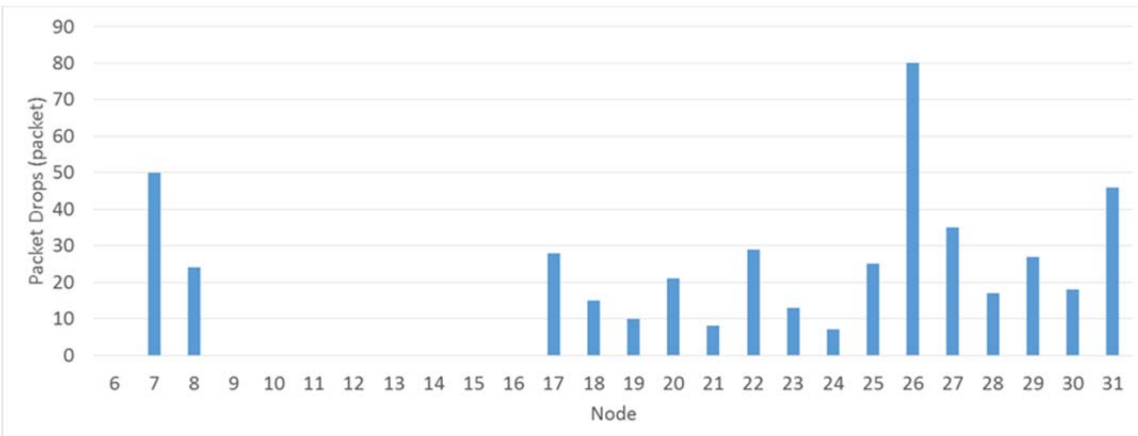

Figure 109. Total Packet Drops for 5.5-Mbps Data Rate in Scenario I

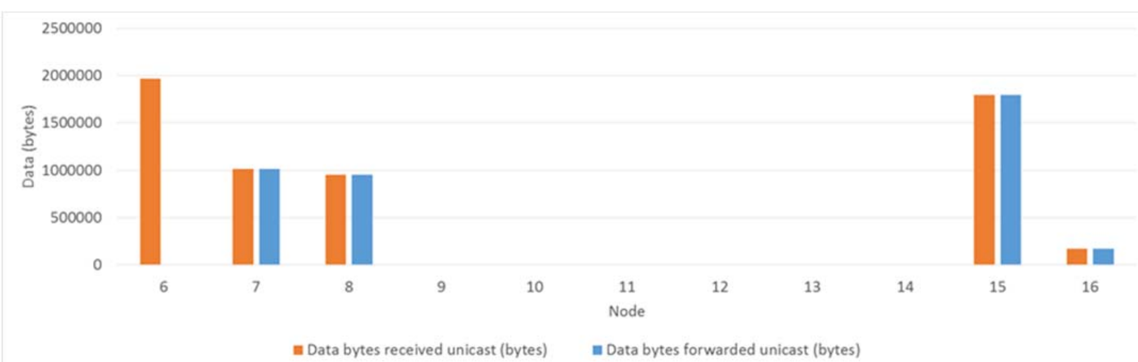

Figure 110. Data Forwarded and Received for 11.0-Mbps Data Rate in Scenario I

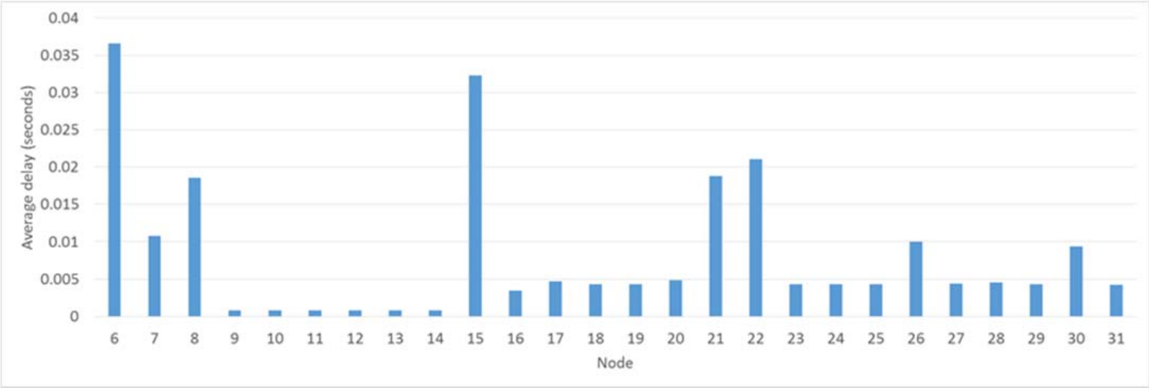

Figure 111. Average Delay for 11.0-Mbps Data Rate in Scenario I

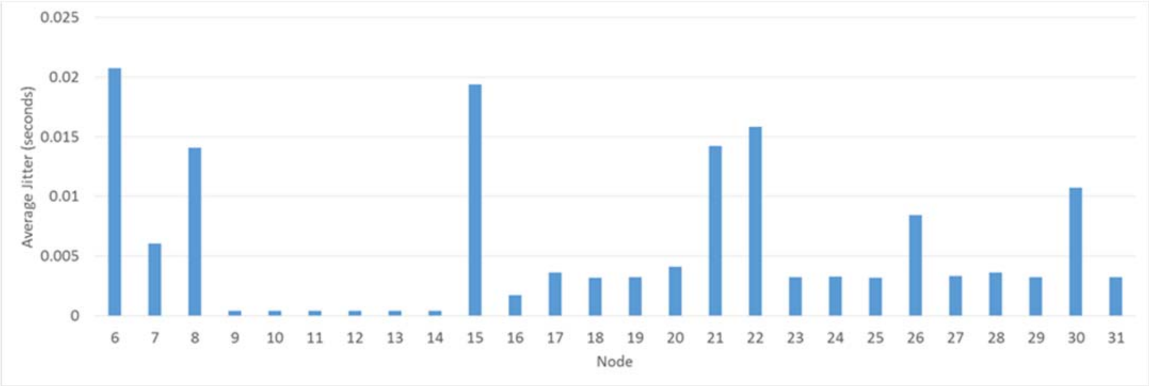

Figure 112. Average Jitter for 11.0-Mbps Data Rate in Scenario I

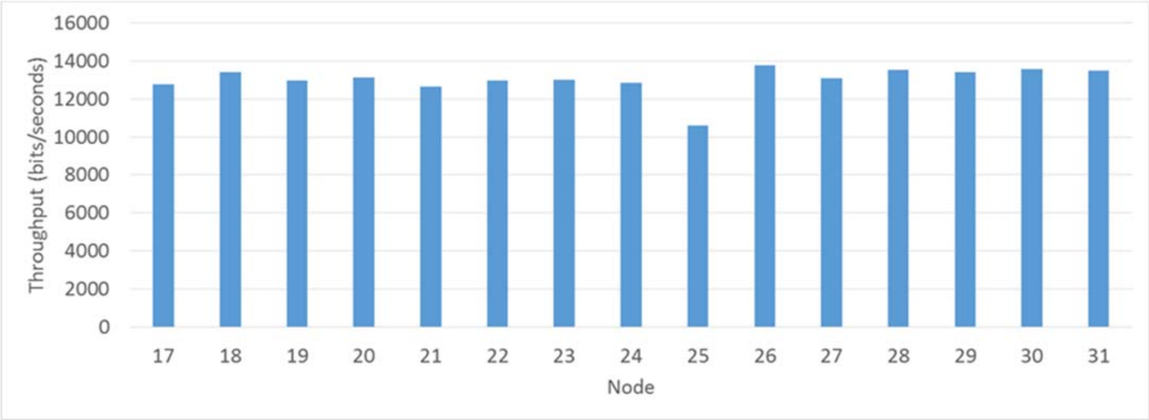

Figure 113. Throughput for 11.0-Mbps Data Rate in Scenario I

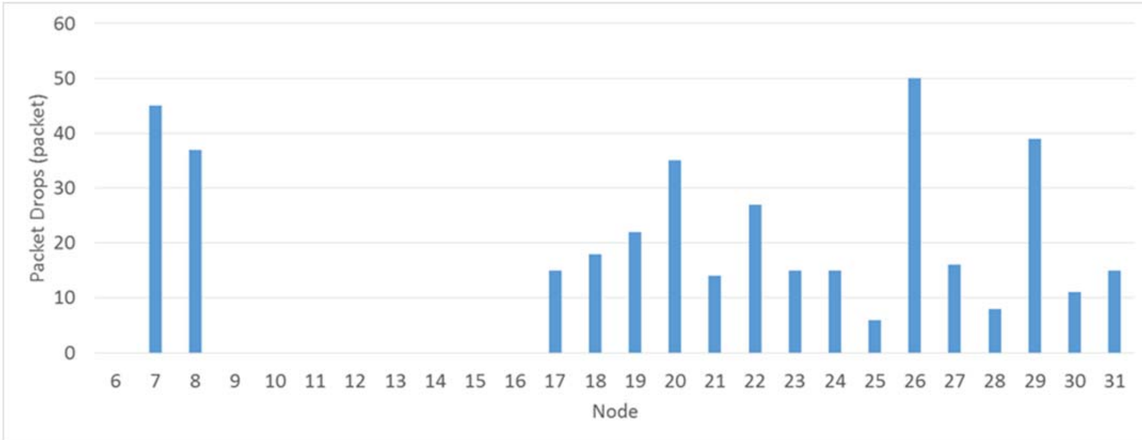

Figure 114. Total Packet Drops for 11.0-Mbps Data Rate in Scenario I

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