The System Design of a Global Communications System for Military and Commercial use Utilizing High Altitude Unmanned Aerial Vehicles (UAVs) and Terrestrial Local Multipoint Distribution Service (LMDS) Sites

The UAV-LMDS system

by

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Abstract

This thesis proposes the design of the UAV-LMDS communication system for military and commercial use. The UAV-LMDS system is a digital, wireless communication system that provides service using unmanned aerial vehicles (UAVs) flying at 60,000 ft. acting as communication hubs. This thesis provides background information on UAV-LMDS system elements, a financial analysis, theory, link budgets, system component design and implementation issues.

To begin the design, we develop link budgets that are used to characterize system parameters. We present detailed antenna designs for the antennas aboard the UAV. We also present communication equipment block diagrams. Included are technical details on military and commercial geostationary satellites used to link transmissions in the system.

Implementation issues in the military system are discussed. Mobility and the effects of vegetation in the propagation path are investigated and a co-channel interference study is done.

This thesis shows that by using UAVs and LMDS, a viable, broadband, wireless communications system can be created for military and commercial use.

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Chapter 1 Introduction

In a translation of the ancient work *The Art of War*, Chinese general, Sun Tzu states, "Hostile armies may face each other for years, striving for the victory which is decided in a single day. This being so, to remain in ignorance of the enemy's condition simply because one grudges the outlay of a hundred ounces of silver in honors and emoluments, is the height of inhumanity [1]." Sun Tzu's *The Art of War* is widely respected and its precepts are used not only in war, but also in sports and finance. In the above quote, Sun Tzu declares that information is needed to spare needless casualties and is crucial to success. No expense should be spared in obtaining information.

Information gives soldiers and commanders an obvious advantage in any situation. Information and its exchange allow fighting groups to increase lethality, decrease losses and meet objectives. Today, sharing information between soldiers is an obstacle that can be solved by the creation of a high-bandwidth digital communications system.

This wireless system can provide many services. Integrating the Global Positioning System (GPS) with the communication system will allow each soldier in a fighting group to know his location relative to friendly and unfriendly forces by way of an arm, helmet or rifle mounted screen. It will give an always-open communication link between soldiers and a direct commander. Commanders can quickly and easily send orders to all subordinates. This system can also create a network between ships, allowing leading ships to quickly share information about over-the-horizon threats to following ships. This communication system can also allow land vehicles such as tanks to share reconnaissance information with commanding officers. Finally, this high-bandwidth system will allow the Navy to rely on its own resources for communications instead of leasing time on commercial satellites.

This high-bandwidth communication system can also be configured to operate in peacetime, supplying communication and multimedia services to private users. The demand for high-speed digital communication links is rising. The use of the Internet and multimedia communications is growing. More and more, businesses value the exchange of digital information. Commerce is becoming increasingly international and geographically dislocated businesses are using real-time video conferencing to link branches. Our society values information and in the coming decades, the exchange of information will be paramount.

The US Navy can pioneer this communication system and the technology can crossover into public use. This system will provide the Navy with a superior fighting advantage and also can provide the means for private individuals and businesses to inexpensively transmit voice, video and data at high data rates. This system will also be able to meet the various communication needs of rural and remote areas. In developing regions, the system can supply residents with basic communications and services such as telemedicine, and educational services. This thesis will provide background information, theory and present a system design, noting issues specific to the military and public systems.

1.1 Basic system idea

Instead of satellites orbiting the Earth or antenna-mounted towers creating the foundation for this communication system design, unmanned aerial vehicles (UAVs) will fly at approximately 60,000 feet and "orbit" land regions to provide service. Communication equipment and antennas will reside onboard each UAV. Several UAVs will service a large geographical region and many users. As each UAV hovers over the region, it will be providing communication service to users below. Users on the ground will transmit to and receive from the overhead UAV. The UAV will direct the transmission to a user within its field of view or if the destination is not in the UAVs sight, the transmission will be handed off in one of three ways. If the destination user is in a neighboring UAV's field of view, the transmission will "hop" from UAV to UAV and then to the destination user. If the user is serviced by a UAV that is out of reach of the originating UAV, the transmission will be linked by geostationary satellite. Finally, in the public system, if the destination user is not serviced by a UAV, the transmission will be linked by conventional methods, e.g. fiber optics or public telephone system.

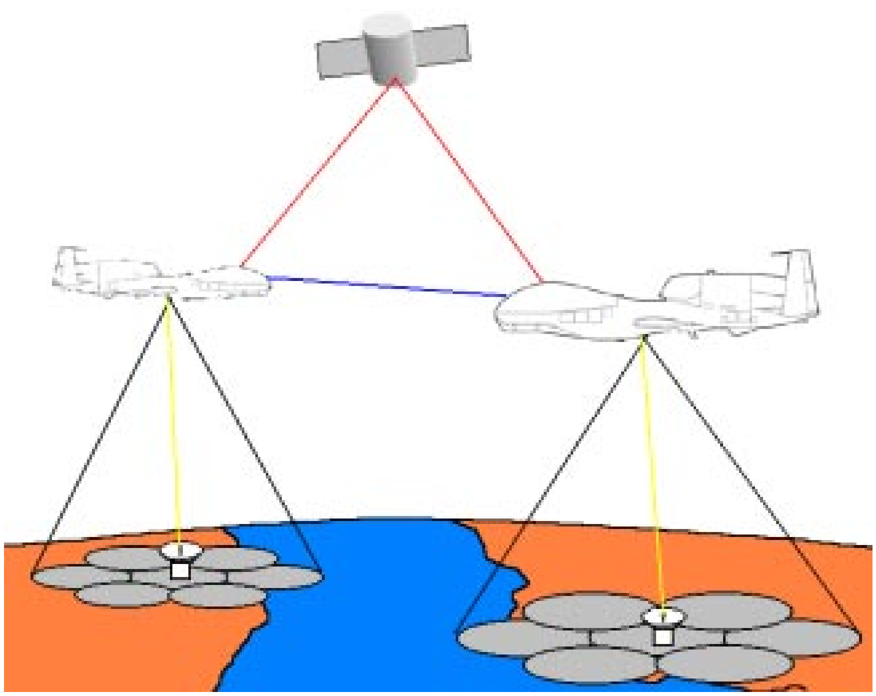

Figure 1.1 UAV-LMDS Communication System

This communication system will deliver completely digital services. Using the LMDS spectrum allows the system to support many users at high data rates. Each UAV will serve approximately 940 users.

1.2 Demand

1.2.1 Military Demand

Military planners predict that military conflicts in the coming years will be much different from traditional warfare of the past. Instead of the massive armored attacks seen in Desert Storm, US forces will be forced to use high technology and information to their advantage to defeat the enemy of the future [2]. Smaller battalions of soldiers will be able to pack more of a punch using information about terrain and friendly and enemy forces. Generals will be given a real-time view of the battle landscape and be able to take action before the enemy. The cornerstone to success of these new military technologies is the ability to communicate and share large amounts of information easily.

1.2.2 Commercial Demand

According to the results of a poll released in June 1999 by InfoBeads, 31.3 million households in the US use the Internet regularly. This number reflects 56% of the US's personal computers, including home, work and self-employed business use computers [3]. Industry analysts predict that this number will continue to grow. Currently, most Internet and digital communications are taking place over telephone lines with modems, where data rates are usually limited to 56 kbps. Observing current trends leads us to conclude that there is significant and increasing demand for high-speed digital communication capabilities, warranting investment in a viable system.

1.3 Competing commercial technologies

There are some existing or emerging technologies that can offer similar services to the commercial UAV-LMDS system. This thesis will attempt to show that the UAV-LMDS system is applicable for a wide range of deployments and could fill a wide gap in providing high-data rate communications worldwide. The following sections briefly describe the competing technologies.

1.3.1 Conventional Modems

Typically, households and businesses that do not have a dedicated data connection utilize conventional modems operating over twisted-pair telephone lines. Modems usually cost as little as $35 for a 56.6 kbps model; Internet service is also relatively inexpensive, generally $200 per year. Conventional modems are convenient to purchase and use and can be used with an existing telephone service. However, with realistic speeds approaching a limit of about 52 kbps, other options are becoming more attractive as data rate demands increase.

1.3.2 Cable Modems

Recently, cable television providers have begun to penetrate the Internet service provider market. Cable providers charge anywhere from $30-$40 per month for their service. Data rates are asymmetrical and also depend heavily on usage. Cable modem providers originally touted 30 Mbps, but current predictions are placing this at a more likely 1.5 Mbps in a practical system. In a practical system, many users share the same connection and the available bandwidth decreases and bit rates decline as the number of users increases. Cable modem data rates are asymmetric, 1.5 Mbps is only for downstream transfers and upstream transmission is much slower. With the one-way nature of the cable system, providing the capability for upstream traffic is difficult. Some systems utilize a separate dial-up connection for transferring upstream, or the entire cable system must be upgraded to support duplex transmission capability. Cable modems currently are making significant progress in the market; however on a large-scale, cable service is simply not available to all locations, especially businesses [4].

1.3.3 ADSL

The Asymmetrical Digital Subscriber Line (ADSL) is a new technology that is being developed by local exchange carriers (LECs). Currently this technology has only been provided in small, trial configurations, and technical issues need to be worked out before ADSL can be deployed in full scale. Small changes in the telephone infrastructure need to be performed, such as the removal of loading coils that improve frequency response in the voice band but increase losses at higher frequencies used by ADSL signals. ADSL uses existing copper telephone lines to supply up to 6.144 Mbps downstream to subscribers. As with cable modems, the upstream and downstream data rates are different, or asymmetrical. Data rates are dependent upon the distance between the subscriber and the telephone switching station. ADSL traffic takes place in the

25kHz to 1.1 MHz band on copper lines. Even at these frequencies losses increase drastically with distance over copper lines, and therefore most telephone companies estimate that only 65 to 75% of their customers are within a distance that can be provided with ADSL service [5][6]. Even this may be too optimistic.

1.3.4 Dedicated T1

The T1 line was developed in the 1960's by AT&T, and was meant to introduce digital voice transmission in an all-analog system. Today, T1 lines are leased to customers who need the guaranteed bandwidth for data transmission. A T1 line is a dedicated data line provided by local telephone companies operating at 1.544 Mbps. Because of the large expense, a T1 line is usually used by large businesses needing constant access to a high-speed line. T1 technology is not applicable for use on a large scale especially to many homes and small businesses, because it is not economical.

1.3.5 Satellite systems

Recently, several satellite-based communication ventures have been launched. These systems are usually designed to provide voice, low-speed data and/or messaging/paging capabilities and are not designed for high-bandwidth data traffic. Iridium is a 66-satellite constellation operated by Motorola spin-off, Iridium, Inc. The Iridium system planned to provide wireless telephone, data and fax service. Iridium's data rates were estimated at 2400 bps, using a personal computer that interfaces with the handheld phone. Teledesic, a gargantuan venture by Bill Gates and Craig McCaw, does plan on providing broadband Internet access, videoconferencing and other data services.

Using 288 Low Earth Orbit (LEO) satellites, Teledesic hopes to provide homes and businesses with 64 Mbps. There are many technical issues still to be solved in providing mass access to data services via satellite. Iridium will most likely be abandoned because of financial troubles and Teledesic's future is uncertain.

1.3.6 UAV-LMDS system compare/contrast

Most of the aforementioned technologies are viable and can find a niche market. Even though each technology can offer data communications, the UAV-LMDS system that is proposed herein can supercede each of these technologies, and with effective marketing, could dominate the field.

The UAV-LMDS system has many technical and economical advantages over competing services. The system can be deployed in varying capacities over a region. This flexibility allows deployment to be gradual and responsive to demand. This offers financial advantages over the satellite networks that require a large initial investment with uncertain returns.

This system also can provide service to wide regions, regardless of their relative location to existing infrastructure. Even in the most remote or most urban, the UAV-LMDS system can be deployed easily.

The UAV-LMDS system also has many advantages over traditional satellite networks, and these may cause a paradigm shift in providing global communications. UAVs stay aloft to provide communications in time shifts. When the UAV is not providing communications, it returns to earth and can be upgraded, refurbished or maintained. This allows the system to adapt to changes and increases reliability.

1.4 Commercial Financial Analysis

Will the UAV-LMDS system offer substantial cost savings over competing technologies? Wired service providers often lament over the "last-mile" problem. The last-mile problem refers to the large cost of wiring high-speed connections (fiber optics, etc) from the customer's home to the central office (CO). The UAV-LMDS is an inexpensive solution to the last mile problem.

We can compare the costs of delivering fiber optic to the home (FTTH) and terrestrial LMDS to the cost of the UAV-LMDS system. If the UAV-LMDS system is providing communications to 1000 households in an area of 5650.4 sq. mi., it would cost between $10-$14 million per UAV, with three UAVs needed. We can estimate that the onboard communication equipment would cost roughly $600,000, per UAV. Also needed is a ground station at an estimated cost of $2 million. To provide communications, the UAV-LMDS system would need roughly $45.8 million. To service the same area (5650.4 sq. mi.) with terrestrial LMDS sites we would need close to 300 towers. The cost of LMDS hubs are decreasing, but a current estimate is around $620,000 each (300 towers = $186 million total) [7]. So many towers are needed because terrestrial LMDS cells have a coverage radius of only 3 – 5 km. However, there is a discrepancy here. Even though it would take 300 towers to service such a large area, each tower could service about 1000 users (300,000 users total). If we wish to compare the cost of servicing 1000 users in a 4-km radius (19.4 sq. mi.) using terrestrial LMDS and the UAV-LMDS system, we can see that the cost savings of the UAV-LMDS system no longer exist. Terrestrial LMDS would be chosen for a high-density deployment, while the UAV-LMDS system would be used for a low-user density deployment, or where tower installations are prohibitive. If we wish to deliver FTTH to 1000 households in a 5650.4-sq. mi. area, we can speculate that we will need to install at least 600 miles of fiber. The average cost of laying fiber optic cable is $150,000 per mile, but is highly dependent upon the terrain involved [8]. This will total $90 million in installation costs. This cost is also dependent upon population density, but reflects the high cost of fiber optic installation.

We can see that the UAV-LMDS system has a low cost, but its class of service is different from others. Ideally, the UAV-LMDS system would be most applicable to a rural region with a low-population density. However, the UAV-LMDS system can be deployed anywhere, without terrestrial obstacles being a concern.

Chapter 2 System Elements

2.1 Global Hawk UAV

Figure 2.1 Global Hawk

There are several UAVs currently in existence that have favorable payload or endurance characteristics. Below is a table summarizing details for several “higher-performance” UAVs.

Table 2.1 UAV Characteristics

UAV NAME	ENDURANCE	PAYLOAD	MAX ALTITUDE	POWER AVAILABLE	CRUISE SPEED
Aerosonde	40 hrs.	2.2 lbs.	20,000 ft.	10 W	70 mph
Altus 2	24 hrs.	450 lbs.	26,000 ft.		
BQM-34	1.25 hrs.	470 lbs.	60,000 ft.		
Chiron	8 hrs.	700 lbs.	19,000 ft		
Darkstar	8 hrs.	1,000 lbs.	45,000 ft.		287 mph
Eagle Eye	8 hrs.	300 lbs.	20,000 ft.		184.12 mph
Firebee	1.25 hrs.	470 lbs.	60,000 ft.		630 mph
Global Hawk	42 hrs.	1,960 lbs.	65,000 ft.		397 mph
Gnat 750	48 hrs.	140 lbs.	25,000 ft.	3kW	53 mph
Hunter	12 hrs.	200 lbs.	15,000 ft.	1.5 kW	102 mph
Pathfinder	16 hrs.	88 lbs.	70,000 ft.		35 mph
Perseus B	72 hrs.	441 lbs.	65,620 ft.	1kW	112 mph @SeaL
Predator	20 hrs.	450 lbs.	26,000 ft.	3 kW	80 mph
Raptor	8 hrs.	75 lbs.	65,000 ft.		284 mph
Shadow 600	14 hrs.	100 lbs.	17,000 ft.	500 W	82 mph
Skyeye	10 hrs.	175 lbs.	18,000 ft.		80 mph
Theseus	50 hrs.	750 lbs.	88,500 ft.		

[9]

Not only does the Global Hawk exhibit some of the best characteristics overall, but this UAV is the focus of Department of Defense (DOD) projects as well. The DOD is using the Global Hawk UAV in reconnaissance and communications programs. Because the DOD uses the Global Hawk for several projects, it can be fitted with systems that enhance its survivability. Aside from flying at a very high altitude, the Global Hawk can carry a jammer and a towed decoy. The towed decoy trails behind the aircraft to attract and be destroyed by missiles intended for the Global Hawk.

The Global Hawk is being used by Defense Advanced Research Projects Agency (DARPA) in a program called Unmanned Aerial Reconnaissance System. In this application the UAV will be deployed over hostile regions to obtain images and relay them back to the operator. This will allow the US military to have near-real time images of the battlefield without risk to human life [10]. The Global Hawk is also being used by the military for providing communications in a program called Airborne Communication Node (ACN). The ACN program plans to provide PCS-like voice and data and militarized tactical paging to soldiers using VHF, UHF and L-Band frequencies [11].

It is clear that the Global Hawk UAV has a significant investment in its success. For this reason and its superior payload capacity, the Global Hawk UAV will be used in this design.

Teledyne Ryan, a division of Northrop Grumman, builds the Global Hawk UAV. The Global Hawk UAV was designed for autonomous military reconnaissance. The UAV can carry a payload of 1960 lbs., has an endurance time of 42 hours and can fly to an altitude of 65,000 ft. [9]. The table below summarizes Global Hawk's characteristics.

Table 2.2 Global Hawk Characteristics

Physical Characteristics	
Height	15.2 ft
Weight	25,600 lbs
Length	44.4 ft.
Fuselage width	4.8 ft
Wingspan	116.2 ft.
Wing Area	540 sq ft.
Performance Characteristics	
Altitude	65,000 ft.
Range	14,000 nm
Endurance	42 hrs.
Cruise Speed	345 kts.
Maximum Speed	>345 kts.
Propulsion	7,050 st

[9][10]

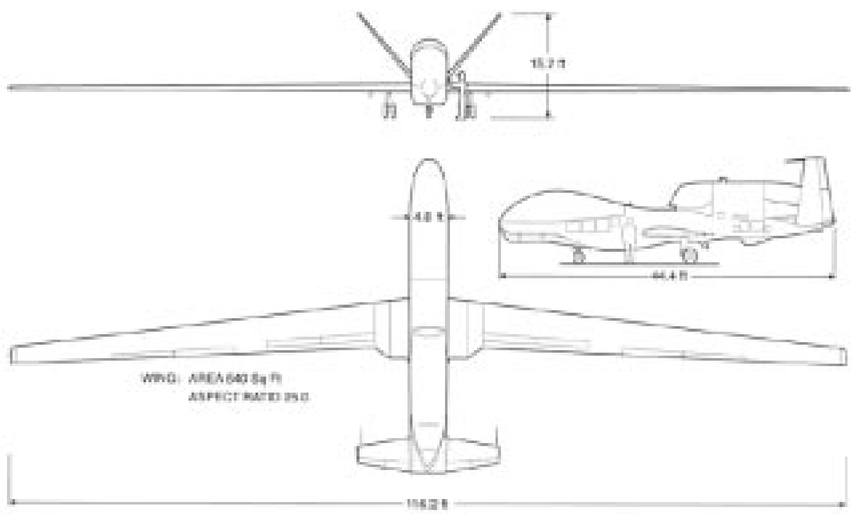

Figure 2.2 Global Hawk Schematic [10]

2.1.1 Flight Plan

The Global Hawk UAVs will be piloted autonomously by operators on the ground. The UAVs will circle at an altitude around 60,000 ft and act as an LMDS hub. Because of the large distance between the user and the UAV, the circling UAV will seem to the ground user as a stationary point and no tracking is required. The radius that the UAV will circle in will be determined from the aircraft's stall speed and the maximum deviation the downlink antennas can compensate for. The UAVs will take-off and land at a dedicated runway, needing roughly 5000 ft to take-off and land [10].

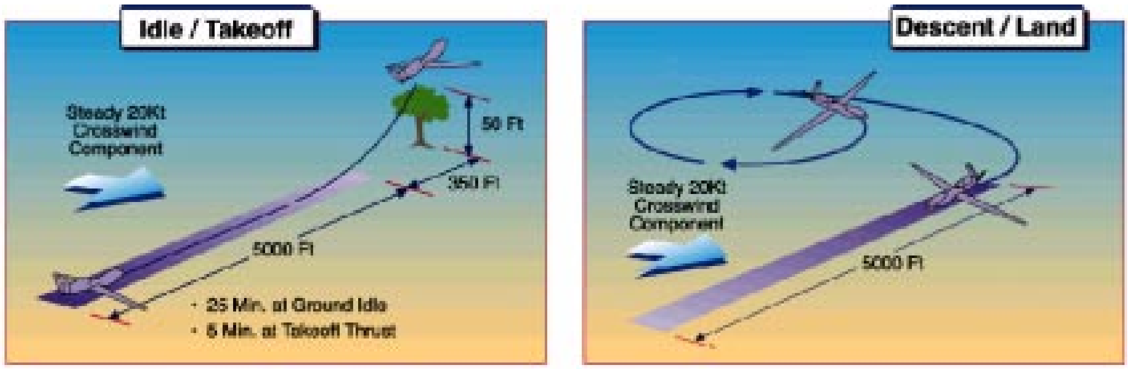

Figure 2.3 Global Hawk Take-Off and Landing [10]

The UAM-LMDS communication system will be available 24 hrs/day; the UAVs will operate in shifts of 24 hours each to provide continuous coverage. A typical flight plan will operate in this sequence: UAV-2 takes off from a UAV-LMDS Airport and flies to its assigned location where UAV-1 is already providing service. UAV-2 would maneuver to its appropriate position and begin to receive transmissions from users on the ground. UAV-1 would then hand-off all call information to UAV-2 and UAV-2 would take over. UAV-1 would then descend from loitering and fly back to UAV-LMDS Airport for a refueling and maintenance check.

2.1.2 Handoff Procedures

When UAV-1 is replaced by UAV-2, a handoff must be accomplished in a seamless manner so existing calls can continue without interruption. While, the UAVs will have the capability to perform the handoff independent of ground control, the handoff will be monitored by ground control. When UAV-1 and UAV-2 are both in a position to offer service the handoff procedure will commence. While UAV-1 is sending and receiving data, UAV-2 will also receive the same transmissions from users, GEOSATs and other UAVs, but will not send any data. This will serve to bring UAV-2 "up-to-date" on the system's activity. As soon as UAV-2 is ready to provide service, UAV-1 will stop outgoing transmissions and then UAV-2 will begin transmission where UAV-1 left off. To avoid a handoff in mid-data packet, UAV-1 will stop transmitting between data packets. UAV-1 will then return to the landing area.

This handoff procedure allows the UAV to be the intelligent entity during the handoff. This allows the user equipment to be inexpensive and, except for a slight pause, the handoff procedure will be transparent to the user.

2.1.3 Commercial Aviation Regulations

The aviation regulations for individual countries are beyond the scope of this thesis. However, since the US maintains some of the strictest aviation guidelines, it is safe to assume that if this system were approved for use in the US it would also be approved for use in other countries of the world.

The Federal Aviation Administration (FAA) controls US airspace and provides specific rules and regulations regarding the use of US airspace. All aircraft must follow the general guidelines outlined in Federal Aviation Regulations (FAR) Part 91 [12]. These guidelines outline basic safety and operational rules that all aircraft operating in US airspace follow. Not many vehicles fly at altitudes around 60,000 – 65,000 ft; the only exceptions are military aircraft like the U2 and the SR71 [13].

During take-off, ascent, decent and landing, the UAV operators will have to adhere to instrument flight rules (IFR) and be in contact with Air Traffic Control (ATC).

The telemetry and nose camera feed provided to the operator will give him/her a pilot's view of the aircraft [14]. Piloting the UAV remotely will be very similar to flying the aircraft in the 1st person. Each UAV will be equipped with standard radar and navigational instruments that the on-ground operator will be able to monitor through telemetry.

2.2 LMDS

Local Multipoint Distribution Service (LMDS) is the name of a new Ka-band spectrum that was auctioned nationally by the FCC in 1998. The FCC has divided the LMDS band into two blocks with one license for each block. Block A consists of 1,150 MHz residing in the 27.500 GHz – 28.350 GHz; 29.100 GHz – 29.250 GHz; and 31.075 GHz – 31.225 GHz bands. Block B consists of 150 MHz, residing in the 31.000 GHz – 31.075 GHz and 31.225 MHz – 31.300 GHz bands [15].

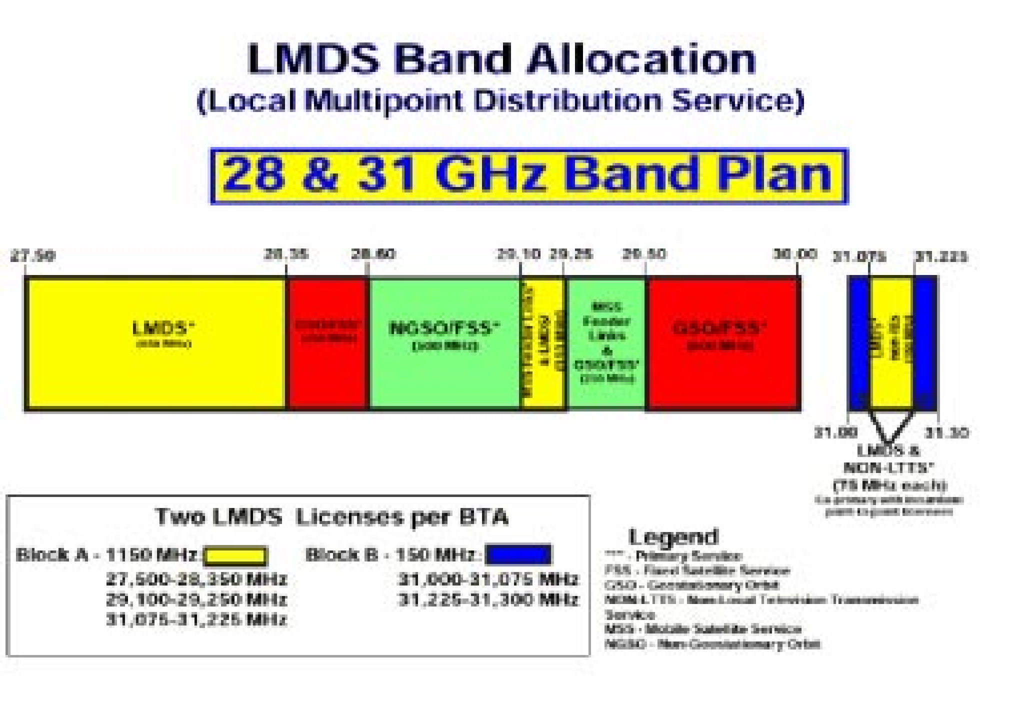

Figure 2.4 FCC Band Plan [42]

LMDS is a very exciting for two reasons; it is the largest amount of spectrum ever auctioned and there are few regulations governing its use [16]. The large amount of spectrum available translates to very high throughput, allowing LMDS operators to provide wireless voice, video and data to homes and businesses. LMDS is made possible not only by the new allocations by the FCC but by recent technological advancements that are responsible for inexpensive hardware that performs well at these high frequencies. Technologies such as Gallium Arsenide (GaAS) integrated circuits (ICs), digital signal processors (DSPs), and MPEG video compression schemes like are just some that are responsible for the viability of LMDS [17].

LMDS has attributes that will be specifically attractive for military use. LMDS antennas are highly directive and signals have a low-probability of intercept. The higher frequencies used (Ka-band) allow smaller and more portable antennas.

There are limitations to LMDS. Its most limiting factor is the range of reliable transmission. At 28 GHz, signals are highly attenuated by rain and foliage. Thus, LMDS is intended to be deployed in a cellular arrangement with typical transmission distances not exceeding 5 km.

2.2.1 Regulations

Before the 28 GHz Ka-Band was auctioned off for LMDS use, it was reserved for Fixed Satellite Service (FSS) and Mobile Satellite Service (MSS). Prior to creating the LMDS bands, the FCC requested LMDS interests and satellite interests to come to an agreement. After years had passed with no progress, the FCC intervened and made the

LMDS spectrum allocations. In certain bands, LMDS has a primary status or co-primary status and shares bandwidth with other services. Details of the specific FCC authorizations are shown in the following table:

Table 2.3 LMDS Frequency Authorization

Frequency Authorization	
Block A Frequencies	
27,500-28,350 MHz	Authorized on a primary protected basis and is shared with FSS systems.
29,100-29,250 MHz	Shared on a co-primary basis with feeder Links for non-geostationary orbit MSS (NGSO/MSS) systems in the band and is limited to LMDS hub-to-subscriber transmissions, as provided in Sec. 25.257 and Sec. 101.103(h).
31,075-31,225 MHz	Authorized on a primary protected basis and shared with private microwave point-to-point systems licensed prior to March 11, 1997, as provided in Sec. 101.103(b).
Block B Frequencies	
31,000-31,075 MHz and 31,225-31,300 MHz	(1) On a primary protected basis if LMDS shares the frequencies with systems licensed as Local Television Transmission Service (LTTS) licensed prior to March 11, 1997, as provided in Sec. 101.103(b).
31,000-31,075 MHz and 31,225-31,300 MHz	(2) On a co-equal basis with systems not licensed as LTTS prior to March 11, 1997, as provided in Sec. 101.103(g).

[18]

We must now consider how these regulations will impact the UAV-LMDS system. Parts of the LMDS spectrum is shared with other users and this may cause conflict. The LMDS spectrum was intended for terrestrial use so the UAV-LMDS system operators would have to petition the FCC for permission to use the LMDS spectrum aerialy. Currently, several petitions are before the FCC asking for permission to use LMDS aerialy. System operators would also have to make special provisions to ensure that its transmissions will not encroach on other non-terrestrial users. In a terrestrial configuration, signals will generally be travelling horizontally, but with an aerial hub and signals travelling vertically, the UAV-LMDS system could have conflicts with satellites using the same frequencies. LMDS licensees are granted primary status in the bulk of the LMDS spectrum, 850 MHz between 27.5 and 28.35 GHz. However, these frequencies are shared with Fixed Satellite Services. LMDS and MSS feeder links have co-primary status in the 29.100 GHz – 29.250 GHz band, only LMDS hub-to-subscriber transmissions are permitted in this band because of possible interference with MSS feeder link space station receivers [15] [19]. Part of Block A, 31.075-31.225 GHz is shared with private microwave point-to-point systems. LMDS frequencies from 31.000-31.075 GHz and 31.225-31.300 GHz are shared with Local Television Transmission Services (LTTS). It is important that an in-depth sharing analysis is done and an agreement reached between FSS, MSS, LTTS, private microwave operators and UAV-LMDS providers before service is initiated.

2.3 Geostationary Satellites

Geostationary Earth Orbit (GEO) satellites have been used for commercial communication since 1965 [20]. GEO satellites are launched into a 35,800 km altitude orbit called the Clarke orbit. In this orbit, the gravitational force of the earth exactly counters a GEO satellite's centrifugal force [21].

Because the GEO satellites are operating at such a high altitude and have such a large illumination footprint, they need more power to communicate with all subscribers. Therefore the GEO satellites must carry larger antenna(s), power reserves and solar panels. Compared to low-earth orbit (LEO) and medium earth orbit (MEO) satellites these large satellites have the highest launch and construction costs. However, the GEO satellites are usually designed to have the longest lifetimes (12- 15 years) [20].

In the UAV-LMDS system, the GEO satellites will link calls that cannot be connected by hand-offs between two or more UAVs that are out of line of sight because of geographic distance. The maximum distance that two UAVs can communicate line-of-sight (LOS) at an altitude of 60,000 ft is 966.1 km (600.2 mi), nadir distances 964.2 km (599.1 mi).

Serving as a communications trunk, the GEOSAT will need to support a high bandwidth. The GEO satellites that augment the UAV-LMDS system will only be acting as "bent-pipes." This means that they will not be processing any information that is sent to them, but rather just relaying information from an originating UAV to the destination UAV. The GEOSATS that will be used with the UAV-LMDS system will use existing satellites and services. Discussed in later sections, the private system will possibly look to service offered by Intelsat and the military system may use Milstar satellites.

2.3.1 Regulations

As with LMDS, there are regulations for the use of spectrum that is reserved for GEOSATs. The spectrum that the UAV-LMDS system will most likely use for communicating with the GEOSATS is the Fixed Satellite Service (FSS) spectrum. The FSS spectrum links GEOSATs and fixed terminals. Typically, these fixed-user satellites support higher bandwidths than the mobile-user satellite constellations. Again, the UAV-LMDS system will have to petition the FCC to use these FSS frequencies from the UAV.

Even though the UAV is mobile, it follows a known path and if the onboard communication equipment meets specifications, a waiver may be granted.

2.4 Global Positioning System (GPS)

The Department of Defense began work on the Global Positioning System in 1972. The satellite constellation was declared officially operational in 1995 and provides positioning to users worldwide. GPS was intended for military use, but the civilian market and user population is growing rapidly. The GPS constellation consists of 24 satellites orbiting at an altitude of 20,300 km.

GPS satellites broadcast two frequencies called L1 (1.57542 GHz) and L2 (1.2276 GHz). The system uses code division multiple access (CDMA) and the two frequencies are modulated with pseudorandom noise codes. L1 is modulated by the coarse acquisition (C/A) code which civilian receivers can decode, while L2 is modulated by the C/A code and the precise (P) code. Military receivers can decode the encrypted P code to obtain a navigation solution with a horizontal accuracy of 22 m. Inexpensive civilian receivers are subject to errors intentionally added by the DOD and produce navigation errors with an accuracy of 100-m [22] [23].

Allies and US forces used over 9000 GPS receivers to aid in navigating the desert during Operation Desert Storm. The GPS receiver is due some of the credit for the US' success in the conflict. By taking GPS a step further and sharing positional information with friendly forces, the friendly fire casualties of Desert Storm could be reduced.

GPS will be integrated into the military receivers in the UAV-LMDS system to provide positioning information to the user and other soldiers using the system.

Receivers have become small and portable and can integrate easily with the communication equipment.

Chapter 3 Theory

3.1 Communication Theory

To design a realistic and fully operational communications system, we turn to communication theory and equations that are solved to determine unknowns in the system design. The first of such equations is the Friis transmission equation. This fundamental equation calculates the spreading or path loss between a transmitter and a receiver. Path loss is a function of transmitted power, receiver and transmitter antenna gains, frequency, and distance between transmitter and receiver.

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \tag{3.1}$$

Where: P_r = Power received [W]
P_t = Power transmitted [W]
G_t = Gain of transmitting antenna [ratio]
G_r = Gain of receiving antenna
λ = Wavelength of signal [m]
R = Transmission distance [m]

Antenna gain is a unitless quantity which describes how focused an antenna's radiation pattern is compared to an isotropic antenna, which radiates equally in all directions. Typically, communications engineering equations are expressed in decibels (dB). A quantity expressed in decibels is shown in the following equation:

$$A = 10 * \log_{10} \left(\frac{P}{P_r} \right) \tag{3.2}$$

The decibel is a logarithmic unit used to compare two power levels [43]. When the value P_r in equation 3.2 is a reference power, such as 1 mW, the decibel value A indicates an absolute value. When absolute values are described, the dB notation is appended. Thus, dBm indicates that the power, *P*, is referred to 1 mW, dBW refers the quantity to 1 W. The Friis transmission equation expressed in dB is as follows:

$$P_r = P_t + G_t + G_r - PathLoss \tag{3.3}$$

Where: $PathLoss = 20 * \log_{10}\left(\frac{4\pi R}{\lambda}\right)$

An important quantity used to characterize transmitters is the Effective Isotropic Radiated Power (EIRP), which is the product of the power transmitted and the transmitting antenna gain, typically expressed in dBW.

$$EIRP = 10 * \log_{10}\left(P_t G_t\right) \tag{3.4}$$

A standard for measuring the performance of a communication system is the received carrier to noise ratio (C/N). This value expresses the ratio of the desired signal power to undesired noise power. If the C/N is too small, a receiver will not be able to detect the transmitted signal. This means that noise is overpowering the carrier. The sensitivity of a system's receiver determines what C/N is necessary for accurate reception. The C/N is calculated from the received power and the system's noise temperature, shown below.

$$\frac{C}{N} = \frac{P_r}{k T_s B} \tag{3.5}$$

Where: k = Boltzmann's constant (1.38×10^{-23} J/K)
T_s = System noise temperature of receiver (K)
B = Noise bandwidth (Hz)

Using the above equation with equations (3.3) and (3.4) we can express the C/N ratio in dB form.

$$\frac{C}{N} = EIRP + G_r - PathLoss - k - T_s - B \tag{3.6}$$

The carrier to noise ratio is a standard performance metric for analog communications systems. For digital communications systems, the probability of bit error, P_b, is a measure of performance. P_b measures the probability that a bit will be received incorrectly. Depending on the type of information to be transmitted, a system will require a certain P_b. If a system is transmitting data, a P_b of 10^{-6} is desired. P_b is calculated from the type of modulation used and the energy per bit per noise density (E_b/N_o), which can be calculated from the C/N. The greater the E_b/N_o, the lower the probability of bit error. In an ideal system, E_b/N_o is calculated like so:

$$\frac{E_b}{N_o} = \frac{C}{N} * \frac{B}{R_b} \tag{3.7}$$

Where: E_b = Energy in a single bit [J]
N_o = Hertz of thermal noise [J*Hz]
C = Carrier Power [W]
N = Noise Power [W]
R_b = Bit Rate [Hz]
B = Bandwidth of Receiver [Hz]

Modulation is a communication technique that is used to place digital or analog information on a carrier for transmission. For example, in an analog system, it allows one to transmit a voice signal that resides in frequencies between 300 – 20,000 Hz on a carrier at any frequency desired. There are three basic forms of modulation, phase, frequency and amplitude modulation. We will only consider digital modulation schemes for the UAV-LMDS system. System designers can pack more information per carrier using aggressive modulation schemes. This is shown in the bandwidth efficiency.

$$\eta = \frac{R_b}{B} \tag{3.8}$$

Where: η = Bandwidth efficiency [bits/s/Hz]
R_b = Bit rate [bits/sec]
B = Bandwidth of transmitted signal [Hz]

In each case the variations in the baseband signal are modulating the phase, frequency or amplitude of the carrier. The *M* of a modulation describes how many amplitude, phase or frequency levels are used in the modulation. For QAM and PSK, the modulation schemes with a higher "*M*-ary" have higher bandwidth efficiency. Shown below are tables for three different digital modulation schemes and their respective characteristics.

Table 3.1: Bandwidth and power efficiency of M-ary QAM

M	4	16	64	256	1024	4096
η	1	2	3	4	5	6
E_b/N_o for BER = 10^{-6}	10.5	15	18.5	24	28	33.5

[24]

Table 3.2: Bandwidth and power efficiency of M-ary PSK

M	2	4	8	16	32	64
η	0.5	1	1.5	2	22.5	3
E_b/N_o for BER = 10^{-6}	10.5	10.5	14	18.5	23.4	28.5

[24]

Table 3.3: Bandwidth and power efficiency of Coherent M-ary FSK

M	2	4	8	16	32	64
η	0.4	0.57	0.55	0.42	0.29	0.18
E_b/N_o for BER = 10^{-6}	13.5	10.8	9.3	8.2	7.5	6.9

[24]

The variable *l* is related to *M* and directly describes the bits per symbol ratio. Digital modulation takes an input bit rate (R_b) and transmits an output symbol rate (R_s) depending on the *M* of the modulation scheme.

$$R_s = \frac{R_b}{l}\ ;\ l = \log_2 M \qquad (3.9,3.10)$$

The final bandwidth of a digitally modulated waveform depends on the type of modulation, the bit rate and what type of pulse shaping is employed. Pulse shaping is the time-domain shape of each digital pulse that is transmitted over the channel. Raised cosine pulse shaping is typically used over other shapes because a smaller transmission bandwidth can be achieved while still avoiding intersymbol interference. The bandpass relationship is given by the equation below.

Raised Cosine Pulse Shaping: $$B = R_s(1+r) \qquad (3.11)$$

Where: B = bandwidth of transmitted signal [Hz]
r = rolloff factor for the Raised Cosine Pulse

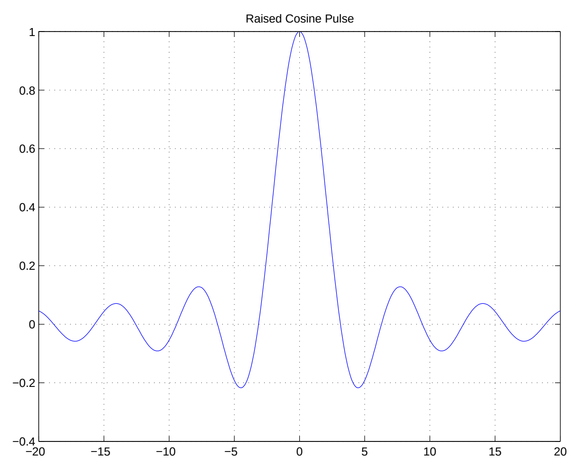

Figure 3.1 Raised Cosine Pulse

In designing a communication system, an engineer must ultimately be concerned with whether or not the system will work. This depends on the expected C/N, calculated from the link budget. Link or power budgets calculate the received C/N based upon transmitted power, antenna gain, path loss and rain attenuation.

3.2 Elements of a link budget

We will now discuss some of the elements of a link budget at 28 GHz. Previously, we have only considered propagation in clear air, but there are several effects that must be considered when calculating received power. Rain attenuates radio signals and is especially harmful to LMDS signals at 28 GHz. It is the rainfall rate, expressed in mm/hr that directly determines propagation effects [25]. There are several models that have been formulated to calculate the amount of attenuation rainfall rates have on a link. We will treat the propagation in the UAV-LMDS system as an earth-space path, utilizing satellite models. We will utilize a method presented by the former International Radio Consulative Committee (CCIR), now known as the ITU-Technical [26]. This CCIR method prescribes seven steps to predict the attenuation exceeded for 0.01% and an additional step to adjust this prediction for other percentages.

To begin calculating the attenuation over a link, one must first find the rain height, h_R. This value is dependent upon the latitude of the receiver and the receiver's look angle. At higher altitudes, temperatures drop and cause rain to freeze. Frozen precipitation does not have a substantial effect upon signal power, therefore we only take into account the signal path that is obstructed by liquid rain. The rain height is calculated thusly:

$$h_R = \begin{cases} 4.0 & 0 < \varphi < 36^{\circ} \\ 4.0 - 0.075(\varphi - 36) & \varphi \geq 36^{\circ} \end{cases} \tag{3.12}$$

Where: h_R = rain height [km]
φ = Latitude of receiver [deg]

Next we calculate the slant path (L_S) using the look angle and the rain height.

$$L_S = \frac{(h_R - h_S)}{\sin(\theta)} \qquad (3.13)$$

Where: L_S = slant path [km]
θ = look angle ($\theta \geq 5°$)
h_s = altitude of receiver

The horizontal projection (L_G) of the slant path is now calculated.

$$L_G = L_S \cos\theta \ \text{[km]} \qquad (3.14)$$

High rain rates are usually localized, while lower rain rates are dispersed over a large region. As the link length grows longer, we must include a reduction factor to take into account varying rain rates over a longer distance. The path length reduction factor for an exceedance of 0.01% is calculated using:

$$r_{0.01} = \frac{1}{1 + 0.045 L_G} \qquad (3.15)$$

Using CCIR rain contour maps, we can find the letter which denotes the climate zone of the region of interest and then using a desired availability of 99.99% (0.01% exceeded), find the rainfall intensity exceeded ($R_{0.01}$) from the CCIR exceedence table (shown below.)

Table 3.5 CCIR Rain climatic zones – rainfall intensity exceeded (mm/h)

% of time	A	B	C	D	E	F	G	H	J	K	L	M	N	P
1.0	<0.5	1	2	3	1	2	3	2	8	2	2	4	5	12
0.3	1	2	3	5	3	4	7	4	13	6	7	11	15	34
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200
0.001	22	32	42	42	70	78	65	83	55	100	150	120	180	250

[26]

From the maps and tables, the value of $R_{0.01}$ can be obtained from which the specific attenuation can be calculated.

$$A_s = aR^b \qquad (3.16)$$

Where: A_s = specific attenuation [dB/km]
a = 4.21 * 10^{-5} * $f^{\,2.42}$
b = 2.63*$f^{-0.272}$
f = (28GHz) frequency [GHz]
(a, b taken from [25])

To calculate the attenuation (*A)* in dB, the specific attenuation must be multiplied by the slant path length and the path length reduction factor [26].

$$A_{0.01} = A_S \times r_{0.01} \times L_S \qquad (3.17)$$

If an attenuation due to a different percentage of exceedance is desired (A_P), simply multiply $A_{0.01}$ by the following expression in the brackets to find an estimate.

$$A_P = \left[0.12\,p^{-(0.546+0.043\log p)}\right]A_{0.01} \qquad (3.18)$$

Where: p = percentage of time rainfall intensity exceeded

The calculated attenuation tells the communication engineer that the link will need a margin of A_P dB added to the link in order to achieve the desired availability. The percentage of time the rainfall intensity is exceeded translates to time a link is unavailable due to excessive rainfall: 0.001% indicates that the link will be unavailable for 5.3 minutes per year; 0.01% means that the link will be unavailable for 53 minutes per year.

Other atmospheric effects that need to be addressed are humidity in the atmosphere and oxygen absorption. Each attenuates radio signals and at the high frequencies that LMDS operates, these have a significant effect. We will add 2 dB of loss to the uplink, downlink and trunk link budgets to account for the attenuation of humidity and oxygen. This amount of attenuation represents the maximum amount of attenuation seen with oxygen in the atmosphere and 100% humidity [13].

The following table shows an example link budget between a user and a UAV to illustrate elements and values (linear and decibel) in a link budget. The values chosen are arbitrary, please see Chapter 4 for actual link budgets and explanations.

Table 3.4 Example Link Budget

Value	**Linear Value**	**Decibel Value**
Transmitter Power	1 W	0 dBW
Transmitter Antenna Gain		36 dBi
Receiver Antenna Gain		24 dBi
Path Length	28, 000 m	
Elevation Angle	40°	
Free Space Attenuation	933.25×10^{-18}	-150.3 dB
R value	42	
Rain Attenuation		28.9 dB
Clear Air Loss	1.584	2 dB
Power Received	380.19×10^{-15}W	-124.2 dBW
Antenna Noise Temp.	290 K	
System Temperature	580 K	
Noise Power	4.17×10^{-15} W	-143.8 dB
C/N	91.2 W	19.6 dB
E_b/N_o	30.9 W	14.9 dB
BER 16-QAM	9.9880×10^{-7}	

3.3 Antennas

A communication system's power budget includes the transmitting and receiving antenna gain. Antenna gain is the directivity of the antenna reduced by losses. Antenna gain describes how focused the beam of an antenna is as compared to an isotropic antenna. An antenna with a larger gain will have a narrower beamwidth. Directivity is the ratio of the maximum radiation intensity to the average radiation intensity and is expressed as:

$$D = \frac{4\pi \times U_m}{W} = \frac{4\pi}{\Omega_A} \tag{3.19}$$

Where: D = Directivity
U_m = Maximum radiation intensity [W/rad^2]
W = Total power radiated [W]
Ω_A = beam solid angle [rad^2]

The above equation shows that the directivity is determined solely from the radiation pattern shape. A radiation pattern describes spatially where the antenna is focusing its radiation. The beam solid angle "is the solid angle through which all the power would be radiated if the power per unit solid angle (radiation intensity) equaled the maximum value over the beam area [27]."

An antenna's maximum effective aperture (A_{em}) describes how much power is collected from a wave with a given incident power density.

$$P_{Am} = S \times A_{em} \tag{3.20}$$

Where: P_{Am} = Maximum available power [W]
S = power density of incoming wave [W/m^2]
A_{em} = Maximum effective aperture [m^2]

For a fixed wavelength, λ; A_{em} and Ω_A are inversely proportional. Increasing an antenna's physical size (which is related to A_{em}) causes the beam solid angle to decrease and the directivity (D) to increase.

$$\lambda^2 = A_{em}\Omega_A\,; \quad D = \frac{4\pi}{\Omega_A} = \frac{4\pi}{\lambda^2}A_{em} \tag{3.21,3.22}$$

Antenna gain is similar to directivity, but gain includes the radiation efficiency of the antenna.

$$G = e_r D \tag{3.23}$$

Where: G = gain of antenna
e_r = radiation efficiency of antenna
D = directivity of antenna

3.4 Noise

Noise is the major limiting element in a communications system [26]. While there are several types of noise, we only need to address thermal noise in this thesis. Thermal noise is a naturally occurring phenomenon in transmission channels and communication equipment operating above absolute 0°K. Thermal noise is caused by random electron motion; as temperature increases, as does electron motion and thus noise increases. Spectrally, thermal noise in the radio frequency spectrum is evenly distributed over the entire frequency spectrum and has a Gaussian amplitude distribution. Thermal noise is directly related to temperature and bandwidth [26].

For a system with a limited bandwidth, noise power is found by:

$$P_n = kTB \tag{3.24}$$

Where: P_n = Thermal Noise power [W]
k = Boltzman's constant [J/K]
B = Bandwidth of system [Hz]
T = Physical temperature [K]

Antenna noise temperature is a function of what the antenna "sees." All objects above 0°K will radiate electromagnetic radiation. Antennas receive this radiation and it results in noise power at the output of the antenna. The sky has a lower temperature than objects (soil, trees, buildings, etc) on earth. In the UAV-LMDS system, the antenna temperature and thus the noise received by the user antennas located on earth will be relatively small. Conversely, the UAV antennas pointed toward the earth will receive a higher noise temperature.

3.5 Other effects

There are other elements of a typical link budget including multipath, atmospheric scintillation, and vegetation losses that have not been considered. Specific system features, including the relatively low altitude of the UAV (compared to the total height of the atmosphere) and because it is not a terrestrial system, means these issues do not apply. In the commercial system, with high-gain, roof-mounted user antennas, and proper mounting procedures, there should not be any vegetation in the path. Similarly, we will specify a relatively high minimum elevation angle for user antennas. This coupled with high gain antennas and with not much atmosphere between the user and the UAV, we can neglect multipath and scintillation effects.

Vegetation effects could come into the picture in the military system due to the range of environments soldiers are subject to. Research has shown that vegetation strongly attenuates and depolarizes signals. Vegetation effects will be further discussed later in the thesis.

3.6 Antenna designs

Several different types of antennas in use in communications systems. The choice of which to use depends on cost, bandwidth, desired polarization, physical limitations, and desired gain. There are two main types of antennas: wire antennas (also called linear antennas) and aperture antennas. Wire antennas include dipoles, monopoles, loops, helices and arrays of these individual antennas. Horns and dish antennas belong in the class of aperture antennas. Wire and aperture antennas have different attributes. Generally, wire antennas have a lighter weight, smaller size, lower directivity and lower cost. Aperture antennas usually are heavier, have a greater directivity and are typically used for frequencies at and above UHF [27].

Antenna arrays are a collection of smaller antennas which when used together simulate a larger antenna. When the currents exciting each element of the array have controlled phases, the array becomes "phased" and the radiation pattern can be scanned electronically. Linear arrays can only be scanned in the plane containing the line of the array, while two-dimensional arrays can be scanned in two dimensions. When the excitation currents have amplitudes which taper towards the ends of the array, the side lobes in the radiation pattern decrease and the beamwidth increases.

Now we present design procedures for antenna arrays and pyramidal horns. Uniformly spaced, non-uniformly excited, linear phased arrays have the following radiation pattern, called the Array Factor (AF):

$$AF = \left(\frac{\sin\left(\frac{n\psi}{2}\right)}{n * \sin\left(\frac{\psi}{2}\right)} \right)^m \tag{3.25}$$

The AF is determined by array attributes: ψ, n, and m. The variable ψ depends upon the wavelength of excitation (λ), spacing between elements (d), phase difference between excitation currents (α) and the angle of observation (θ).

$$\psi = \beta d \cos\theta + \alpha \tag{3.26}$$

The value *m* relates to the degree of taper in the current distribution over the array elements and *n* can be related indirectly to the number of array elements. The actual number of elements in a non-uniformly excited array is expressed as such:

$$N = m*(n-1)+1 \tag{3.27}$$

The total radiation pattern of an array is the multiplication of the element pattern by the AF. If the individual element is a dipole, the element pattern is expressed in spherical coordinates below and looks like a toroid (or donut):

$$\frac{\cos^2\left(\frac{\pi}{2}\sin(\theta)\cos(\varphi)\right)}{\left(1-\left(\sin(\theta)\cos(\varphi)\right)^2\right)\sin(\theta)} \tag{3.28}$$

Pyramidal horns are the most popular form of the rectangular horn antenna [27]. The aperture of the pyramidal horn can be flared in either principal plane, narrowing the beamwidth in that plane. A pyramidal horn has the following physical form:

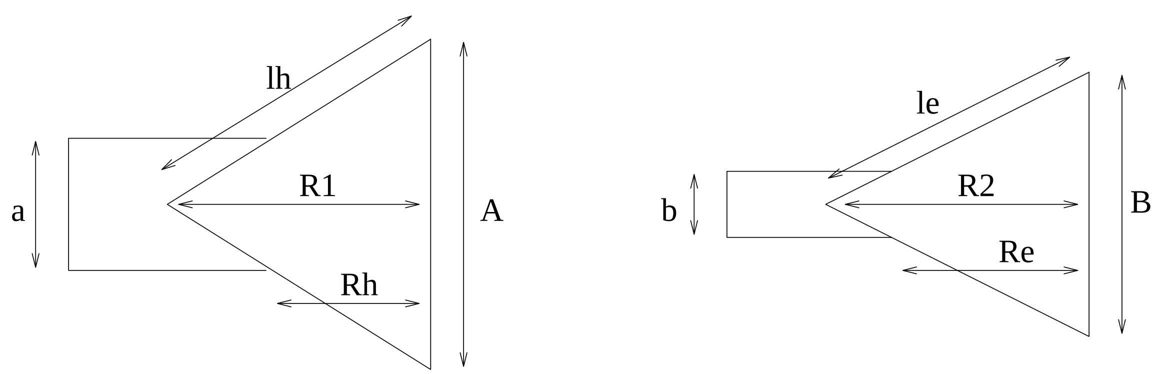

Figure 3.2 Pyramidal Horn Diagram

The design approach presented here is a slight modification of the optimum horn design procedure presented in [27].

Knowing the desired antenna beamwidths we can estimate the gain of the antenna using the following equation:

$$G \approx \frac{26000}{HP_E^{\circ} HP_H^{\circ}} \tag{3.29}$$

Where: G = Gain of the horn
HP_E = Half-power beamwidth in the E-plane in degrees
HP_H = Half-power beamwidth in the H-plane in degrees

Specifying the gain and WR28 waveguide dimensions, a = 0.007112 m and b = 0.003556 m, we can solve the following equation for A, using 0.51 for the aperture efficiency (ε_{ap} = 0.51).

$$A^4 - aA^3 + \frac{3bG\lambda^2}{8\pi\varepsilon_{ap}} A = \frac{3G^2\lambda^4}{32\pi^2{\varepsilon_{ap}}^2} \tag{3.30}$$

Next we can solve for the other dimensions of the horn, B, R_1, R_2, l_H, l_E, R_H, R_E using the following equations:

$$B = \frac{G\lambda^2}{2.04\pi A},\ R_1 = \frac{A^2}{3\lambda},\ R_2 = \frac{B^2}{2\lambda},\ l_H = \sqrt{{R_1}^2 + \left(\frac{A}{2}\right)^2},\ l_E = \sqrt{{R_2}^2 + \left(\frac{B}{2}\right)^2},$$

$$R_H = \frac{R_1(A-a)}{A},\ R_E = \frac{R_2(B-b)}{B} \qquad \text{(3.31, 3.32, 3.33, 3.34, 3.35, 3.36, 3.37)}$$

A final check can be done by verifying that R_E equals R_H, and solving the following equations to verify that s = 0.25 and t = 0.375

$$s = \frac{B^2}{8\lambda R_2},\ t = \frac{A^2}{8\lambda R_1} \qquad \text{(3.38, 3.39)}$$

3.7 Multiple Access Techniques

With a large bandwidth of contiguous 850MHz available, the LMDS spectrum seems boundless. However, to maximize the number of users and their individual bit rates, an appropriate multiple access scheme must be chosen. There are three general types of multiple access techniques in practice: frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA.) These techniques, and variations/combinations of them, allow many users to share bandwidth.

The choice of a particular multiple access scheme depends on many characteristics of the system, including; type of information to be transmitted, how bursty or continuous the information is, and the number of users in the system. Access assignments can also be dynamic or static. Dynamic access, also known as demand access, allows users to be assigned chunks of time or frequency depending on their need. This technique allows the system resources to be fully used at all times.

3.7.1 FDMA

Frequency Division Multiple Accessing has served as the main multiple access scheme for the past 25 years in satellite service [26]. FDMA divides the total system bandwidth into smaller segments, or channels, and assigns each to a particular user. In this fashion, several users each get an assigned channel and every user can access parts of the system bandwidth simultaneously. The obvious drawback with FDMA is that the total system bandwidth is not available to each user.

Implementing FDMA requires system designers to divide the system bandwidth by the number of users, and include guard bands. Guard bands are unused parts of the spectrum that lie between individual users' bands and are used to prevent interference between users. The size of guard bands determines the bandwidth efficiency of an FDMA system and is determined by system characteristics. When the guard band becomes excessive, bandwidth is wasted, and spectral efficiency is compromised.

3.7.2 TDMA

With TDMA, every user is able to transmit over the entire system bandwidth, but only during an assigned time slot. Whereas FDMA assigns users a frequency slot, TDMA assigns users a slice of time. During each user's time slot, the entire system bandwidth is used. TDMA is useful only for digital systems [26]. TDMA is ideal for use in a demand access arrangement because of the flexibility of time assignments.

Analogous to guard bands in FDMA, TDMA needs guard times to prevent transmissions from overlapping. Also with TDMA, a preamble is necessary before each user's transmission. A preamble contains syncing information for the demodulators. The length of the guard and preamble times determines the efficiency of the system.

3.7.3 CDMA

Code Division Multiple Access is different from the previously discussed multiple access schemes. Instead of making discrete divisions in frequency or time, CDMA allows each user to broadcast over the same spectrum. Without a technique called spread sprectrum, this system would not work. In Direct Sequence CDMA, each user's information signal is spread using a large bandwidth pseudorandom noise (PN) code, making the final bandwidth of the signal to be transmitted 10 to 100's of times greater than the original information bandwidth. Receivers can identify and decode each user by their unique pseudorandom code. CDMA offers low probability of intercept and resistance to jamming that makes it attractive for military use. Recently however, CDMA is being used in commercial cellular systems. CDMA is the multiple access scheme being used in the IS-95 cellular standard.

Another type of CDMA multiple access scheme is a frequency-hopped signal. Instead of a large bandwidth signal spread with PN code, the original signal hops or changes frequency based upon a unique PN code. A receiver used in a frequency-hopped system has a priori knowledge of this code. Accordingly, it hops the same pattern to correctly receive and decode the transmitted signal

3.7.4 Comparison of MA techniques

TDMA, FDMA and CDMA are all viable solutions to the multiple access problem. Each has its specific advantages and disadvantages. FMDA is much less complex than TDMA and CDMA. But, it is relatively simple to arrange TDMA in a demand access configuration. Below is a comparison of each technique in tabular form:

Table 3.6 Multiple Access Schemes

MA Technique	**Advantages**	**Disadvantages**
FDMA	Mature Technology No timing needed	Can be inflexible to system changes Inflexible to traffic load
TDMA	Maximizes transponder power, no intermodulation backoff Flexible to dynamic access Interfaces well with digital networks Error control and source coding compatible	Complexity with timing Buffers needed
CDMA	No timing or frequency control needed Maximize # of users with voice traffic Soft capacity limit Inherent resistance to multipath fading	Power control needed Inefficient with high bandwidth users

[24][26]

3.8 Frequency Reuse

To increase the number of users supported by a communications system, designers can reuse frequencies under certain conditions. This technique raises the available bandwidth. In order to implement frequency reuse, links that use the same frequency must be located a distance apart. This prevents interference from nearby users on the same frequency. Figure 3.3 below shows a frequency reuse pattern for a cellular system.

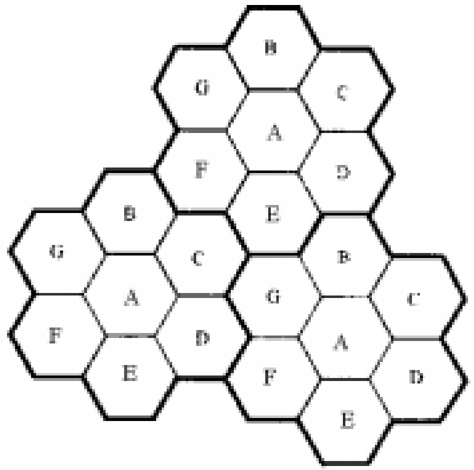

Figure 3.3 Cellular Frequency Reuse Pattern

Chapter 4 Link Design

In this section we will make some initial system choices and present link budgets. From these link budgets we can determine needed antenna gains and other system parameters. We will discuss multiaccessing issues and frequency allocations. Unless stated otherwise, the link budgets will apply to the military and commercial system. The link budgets will be calculated for a UAV-LMDS system operating in Blacksburg, Virginia. Blacksburg is located at 37.23°N, 80.42°W at an altitude of 620 m. From CCIR rain region maps, Blacksburg, Va. is in rain region “K”.

4.1 Initial Choices

To begin the link design, we first need to fix several parameters. We would like to specify that all users of the UAV-LMDS system have a minimum elevation look angle of 15°. This look angle will enable users to avoid most vegetation. Knowing that the UAV flies at an altitude of 60,000 ft (18,300 m), we then can calculate the area of coverage: 5650.4 sq. mi. We decide to divide the 5650.4 sq mi. that the UAV covers into 19 equal beam footprints under the UAV. Fewer beams will mean that a more complex TDM technique will need to be employed because more users will be sharing a single beam. More beams will increase the number of antennas and feeds thus increase the UAV payload’s size, weight and complexity. This equal-sized footprint arrangement means that beams near the perimeter of coverage will have smaller beamwidths and larger gains than beams near the center of coverage. The onboard transmitters will have to compensate for these differences in gain. Knowing the geometry of the downlink beams and using equation (3.29) we can get an idea of the necessary antenna gains.

These antenna gain estimates will be used in the following downlink link budgets. For more information on the UAV uplink and downlink antenna configurations, please see section 5.1.1.1.

We also want the user equipment to be as simple and inexpensive as possible. In the military system, this means that it will be lighter and smaller. For the commercial system, this translates to lower cost for the user. We will fix the user transmit power to 1 W. In all link budgets, we assume the low-noise-amplifiers (LNAs) have a 3-dB noise figure.

4.2 Multiaccessing and Frequency Plan

The choice of multiple access schemes depends on many parameters in the system. The UAV-LMDS system will provide voice, video and data to subscribers. The system characteristics are as follows: many users, high data rate, and both bursty and continuous transmissions.

We will first consider CDMA. CDMA has many benefits as previously outlined. However, when analyzing a CDMA scheme for use in the UAV-LMDS system, we find that CDMA is very inefficient when applied to the UAV-LMDS system. CDMA is not able to support many users at a high-bandwidth. Using the following equation (4.1) from [24] we can perform a rough calculation to gauge the performance of CDMA.

$$P_b = Q\left(\sqrt{\frac{3N}{K-1}}\right) \tag{4.1}$$

Where: P_b = Probability of bit error
N = Spreading factor (BW/R_b)
K = Number of users

This equation assumes the system is interference limited and operating in an additive white Gaussian noise (AWGN) channel [24]. We specify that P_b be equal or less than 1×10^{-6}. Assuming that the users transmit at 1.54 Mbs in the entire 850 MHz, we calculate N to be equal to 550.5. We find that roughly 24 users would be able to utilize the system simultaneously. CDMA works best when the information bandwidth is small e.g. voice and the resulting coding gain (total bandwidth/bit rate) is large.

The ideal multiple access technique for this system is a frequency division multiple access/time division multiplexing (FDMA/TDM) scheme. The entire 1300 MHz of LMDS spectrum will be divided into several blocks with different uses. (see Figure 4.1)

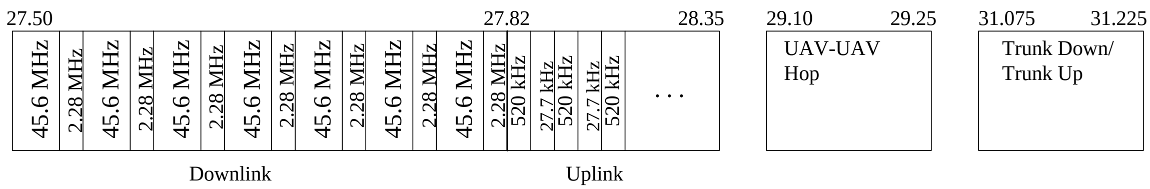

Figure 4.1 Frequency Plan

The UAV-LMDS system will use the continuous block of 850 MHz (27.50 to 28.35 GHz) for user to UAV and UAV to user traffic and divide this into up-link and downlink blocks. The uplink segment (513.24 MHz) will consist of 940 blocks totaling 520 kHz each with 27.7 kHz between each user as a guard band. FDMA was chosen on the uplink to simplify the user equipment. The downlink segment (335 MHz) will be divided into 7 blocks each 45.644 MHz with 2.28 MHz of guard band between each block. Each of these downlink blocks will be reused, with a 1:7 frequency reuse and 19 beams, effectively raising the downlink bandwidth to 867.24 MHz. Reusing these frequencies allows the system to support more users. With the highly directive nature of the LMDS antennas, frequency blocks can be reused in different regions. Frequency reuse cannot be utilized on the up-link because there is no spatial diversity at the UAV's receiver(s). Since each user is given a specific frequency segment in the uplink block, we can avoid complicated logon procedures.

We will allow 940 users to use the system simultaneously, but this number of simultaneous users will cause the total downlink bit rate (including coding bits) to be 2.5 Mbps. Higher downlink bit rates will be achieved when there are less than 940 simultaneous users. Because of the demand access arrangement on the downlink, as the number of users decreases the downlink bit rate will increase while the uplink bit rate will remain the same.

After presenting itself to the system on its designated uplink segment, the user will be assigned a downlink time slot for use. The length of this time slot will be chosen to maximize the usage of the downlink spectrum while giving all other users equal privileges. Periodically, each user's time slot will be adjusted to compensate for a changing number of users. This dynamic access arrangement will allow for greater downlink bit rates (maximum of 135 Mbps with 16-QAM) as the number of users decreases.

The UAV-UAV hopping transmissions will be limited to the 150 MHz block between 29.10 and 29.25 GHz. This was decided to minimize conflict with existing users of the LMDS spectrum. This spectrum is shared with MSS feeder links and the horizontal transmissions of the UAV-to-UAV hops will be less likely to interfere with the vertical transmissions used by the MSS links (See Figure 2.4.)

The trunk uplink and downlink will occupy the 150 MHz of LMDS spectrum between 31.075 and 31.225 GHz. Site planning will have to be done to assure that this link will not interfere with coprimary users.

The spectrum used to link communications between GEOSATs and UAVs will ultimately be decided by what the existing GEOSAT is using. However, one of the benefits of the LMDS spectrum is its proximity to the geostationary orbit/FSS spectrum. This spectrum totals 750 MHz between 28.35 to 28.60 GHz and 29.50 to 30.00 GHz. This proximity can simplify the system because the LMDS equipment may be used for the GEOSAT link. The proximity of the frequencies also simplifies frequency conversion. If the military system uses the Milstar system, the UAVs will need to transmit at 44 GHz and receive at 20 GHz.

4.3 Coding and Bit Rate

We can get an idea of the payload bit rate versus the total bit rate by looking at how coding is accomplished in similar systems. Forward error correction (FEC) coding is done in communication systems to identify and correct bit errors in a digital transmission. FEC coding is accomplished by adding redundant bits to the payload data [28]. There are two approaches to FEC coding, block and convolution codes. Block codes divide the data stream into blocks that are coded as a whole. Convolution codes do not make such divisions in the data stream; instead the data stream is continuously coded [24]. Even though we will specify a BER of 10^{-6} in the link budgets, we would like to briefly investigate the effect of FEC coding on bit rates because received errors can be corrected instead of having to use system resources to retransmit corrupted transmissions.

It is safe to assume that the terrestrial LMDS has similar propagation characteristics to the UAV-LMDS system. Looking at chipsets offered by Broadcom and used in terrestrial LMDS communications, we discover that a Reed-Solomon (N, K) = 204,188: t=8 block code is used for FEC [29]. N data bits are input to the block coder and K bits are returned on the output. N – K redundant bits are added to the payload data. If we a providing a total bit rate of 1.54 Mbs on the uplink of the UAV-LMDS system and using a Reed-Solomon (N, K) =204, 188 code, the actual payload data rate is 1.419 Mbs. Assuming the downlink uses the same code, we will provide 2.3 Mbs payload data rate when the total data rate is 2.5 Mbs.

4.4 Modulation

In the link budgets, we will investigate M-ary QAM and QPSK. M-ary QAM balances efficient use of bandwidth with acceptable power requirements. 16-QAM is practical for use in customer equipment and has higher bandwidth efficiency than QPSK. For trunking links, like the inter-UAV link and the trunk downlink and trunk uplink, a more aggressive, i.e. more bandwidth efficient scheme will need to be chosen. We will investigate transmission using 64-QAM and 256-QAM. A choice will be made in the link section and will depend on the quality of the link, transmission power and antenna gains. This more aggressive modulation scheme can allow the link to support more throughput, enabling the inter-UAV link and trunk links to operate as high-capacity links.

An aggressive modulation scheme must be chosen for the GEOSAT link as well. Typically the travelling wave tubes in the transmitters aboard satellites operate non-linearly, and are not suited to amplitude modulation (AM). The GEOSAT link will require a modulation scheme based upon phase shift keying (PSK), most likely QPSK. The choice of modulation scheme depends upon what is used by the satellite. Generally, PSK is less bandwidth efficient than AM, so more bandwidth may be needed to allow the GEOSAT-UAV link to carry large amounts of data.

4.5 Implementation Margins

There are several ideal conditions that are usually assumed when using communications equations to model systems. Conditions such as ideal matched square-root raised cosine filters, zero intersymbol interference, no clock jitter and ideal modulation cannot be attained in practice. To address these imperfections, implementation margins will be added to the link budgets. The implementation margins represent losses in the system. For bit rates around 1 Mbs, we will use an implementation margin of 1 dB, for greater bit rates around 100 Mbs, we will use an implementation margin of 2 dB.

4.6 Uplink - User-to-UAV

The objective for the uplink budget is to characterize the link and determine necessary antenna gains and transmitter powers. The link restrictions are as follows: transmit power equal to 1W and transmission bandwidth restricted to 520kHz. Using equations (3.9), (3.10), (3.12), we can see that we will be able to support a bit rate of 1.54 Mbs inside 520 kHz using 16-QAM, but QPSK will need over 1 MHz to support the same bit rate. Thus, we can rule out QPSK. We would like to obtain a BER of 10^{-6} for all users, but users will experience varying reliability due to excess rain attenuation depending on their location. The closer a user is to the UAV nadir point, the better the reliability. The worst case scenario deals with a user on the perimeter of coverage with a look angle of 15°, while the best case involves a user directly underneath the UAV. Shown below are the tabulated link budgets for the best and worst case scenarios.

Table 4.1 Uplink Link Budget, Worst Case

UAV altitude	18,300 m (60,000 ft)
Path Length	66,700 m
Elevation Angle	15 °
Center Frequency	28 GHz
Receiver Antenna Gain	24 dB
Off-boresight	-3 dB
Transmit Power	1 W
Transmit Antenna Gain	36 dB
Bit Rate	1.54 Mbs
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-157.9 dB
Percentage of time out due to excess rain	0.0773 %
Rain Margin	20.3 dB
Power Received	-124.2 dB
System Temperature	580 K
Bandwidth	519.75 kHz
Noise Power	-143.8 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	9.8877×10^{-7}

Table 4.2 Uplink Link Budget, Best Case

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	28 GHz
Receiver Antenna Gain	24 dB
Transmit Power	1 W
Transmit Antenna Gain	36 dB
Bit Rate	1.54 Mbs
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-146.3 dB
Percentage of time out due to excess rain	0.00123%
Rain Margin	34.8 dB
Power Received	-124.2 dB
System Temperature	580 K
Bandwidth	519.75 kHz
Noise Power	-143.8 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	9.1538×10^{-7}

During heavy rainstorms, perimeter users may experience outages. Statistically, based upon the rainfall intensity exceeded for this region (Blacksburg, VA), this will occur 0.0523% of the time or about an average of 5 hours per year. However, users directly beneath the UAV will have reliabilities on the order 99.9987%. On average, outages will occur for roughly 7 minutes per year. The closer a user is to the nadir point, the greater the reliability of the link. Both links will operate with very low bit error rates in clear weather.

4.7 Downlink

These link budgets were calculated attempting to match the downlink availability to the availability of the user's uplink. It is logical that users' uplink and downlink should have the same availability. When this was not possible, the availability was decreased slightly until the UAV's transmit antenna gains and power levels were reasonable. There will be three link budgets done for the downlink. Since we specified 19 downlink beams with equal footprint areas, there needs to only be three different antenna types, the perimeter, middle and center beams. Further explanation and diagrams can be found in the antenna design section.

Each downlink beam is restricted to a bandwidth of 45.644 MHz and can be shared by users using a TDM scheme. We did not specify any downlink power restrictions but we would like to keep the downlink power at reasonable levels. Again, using equations (3.9), (3.10), (3.12), we can see that we will be able to support a bit rate of 135 Mbps in 45.644 MHz using 16-QAM. If 53 users were in a beam each user would be able to receive at 2.5 Mbps.

4.7.1 Downlink – Perimeter user

Table 4.3 Downlink Link Budget, Worst Case, Perimeter user

UAV altitude	18,300 m (60,000 ft)
Path Length	66,700 m
Elevation Angle	15°
Center Frequency	28 GHz
Receiver Antenna Gain	36 dB
Off-boresight	-3 dB
Transmit Power	27 W
Transmit Antenna Gain	25 dB
Bit Rate	2.5 Mbs (135.24 Mbs)
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-157.9 dB
Percentage of time out due to excess rain	0.0956 %
Rain Margin	18.5 dB
Power Received	-107.0 dB
System Temperature	345 K
Bandwidth	861.207 kHz (45.6 MHz)
Noise Power	-126.6 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	9.7622×10^{-7}

4.7.2 Downlink – Middle User

Calculating the corresponding uplink budget for the middle user, we find that with a 1 W transmit power there is a 0.01 percentage of rain outage. We cannot match this availability with reasonable downlink EIRP so we decrease the availability slightly.

Table 4.4 Downlink Link Budget, Worst Case, Middle user

UAV altitude	18,300 m (60,000 ft)
Path Length	39,600 m
Elevation Angle	26.3°
Center Frequency	28 GHz
Receiver Antenna Gain	36 dB
Transmit Power	27 W
Transmit Antenna Gain	16 dB
Off-boresight	-3 dB
Bit Rate	2.5 Mbs (135.24 Mbs)
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-153.3 dB
Percentage of time out due to excess rain	0.0736 %
Rain Margin	14.0 dB
Power Received	-107.1 dB
System Temperature	340 K
Bandwidth	861.207 kHz (45.6 MHz)
Noise Power	-126.7 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	9.7629×10^{-7}

4.7.3 Downlink – Center User

Calculating the corresponding uplink budget for the middle user, we find that with a 1 W transmit power there is a 0.001 percentage of rain outage. We cannot meet this uplink availability with reasonable downlink power so we decrease the downlink availability.

Table 4.5 Downlink Link Budget, Worst Case, Center user

UAV altitude	18,300 m (60,000 ft)
Path Length	22,100 m
Elevation Angle	52.9374°
Center Frequency	28 GHz
Receiver Antenna Gain	36 dB
Transmit Power	27 W
Transmit Antenna Gain	6.8 dB
Off-boresight	-3 dB
Bit Rate	2.5 Mbs (135.24 Mbs)
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-148.3 dB
Percentage of time out due to excess rain	0.0513 %
Rain Margin	10.3 dB
Power Received	-107.5 dB
System Temperature	310 K
Bandwidth	861.207 kHz (45.6 MHz)
Noise Power	-127.1 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	9.9342×10^{-7}

4.8 Hop-link

The objective for the UAV Hop-link budget is to characterize the link and solve for the necessary antenna gains, transmitter powers and modulation type. We have determined that the maximum distance between two UAVs is 600 mi (965.9 km). We would like to obtain a BER of 10^{-6} for the link with a reasonable transmission power. The UAVs fly above liquid precipitation so rain will not affect link quality. The main obstacle to this link is sky noise. Since the antennas have a 0° elevation angle, the antenna temperature seen at 29 GHz is roughly 280 K [30]. Again, we will assume the LNAs have a 3-dB noise figure. We will present two link budgets, one for 64-QAM and the other for 256-QAM. With a 150 MHz bandwidth we can provide a bit rate of 666.67 Mbs with 64-QAM and 888.89 Mbs with 256-QAM.

Table 4.6 Hop Link, 64-QAM

Path Length	965,900 m
Center Frequency	29.175 GHz
Receiver Antenna Gain	38 dB
Transmit Power	38.2 W
Transmit Antenna Gain	38 dB
Off-boresight	-3 dB
Bit Rate	666.67 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-181.4 dB
Power Received	-94.6 dB
System Temperature	570 K
Bandwidth	150 MHz
Noise Power	-119.3 dB
C/N	24.7 dB
E_b/N_o	18.2 dB
Bit Error Rate (64-QAM)	9.7125×10^{-7}

Table 4.7 Hop link, 256-QAM

Path Length	965,900 m
Center Frequency	29.175 GHz
Receiver Antenna Gain	38 dB
Transmit Power	196.5 W
Transmit Antenna Gain	38 dB
Off-boresight	-3 dB
Bit Rate	888.89 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-181.4 dB
Power Received	-87.5 dB
System Temperature	570 K
Bandwidth	150 MHz
Noise Power	-119.3 dB
C/N	31.8 dB
E_b/N_o	24.1 dB
Bit Error Rate (256-QAM)	9.9838×10^{-7}

Comparing the two modulation choices shows us that if 64-QAM is used, transmitter power is lower as is antenna gains and bit rate. 256-QAM requires more transmitter power and more complex modulators and demodulators are necessary to support 256-QAM. The 196.5 W necessary to support 256-QAM is unreasonable, therefore we will use 64-QAM for the Hop Link.

4.9 Military GEOSAT Links

The military GEOSAT link budget will be calculated using the Milstar system. Details of the Milstar system can be found later in the thesis. This link will be used to carry communications to and from remote commanders and also can be used to carry command and control information to the UAV. Like the UAV hop link, the GEOSAT link does not have liquid rain in the path to affect reliability. As stated in the GEOSAT orbit section, the Milstar links operate at 44 GHz uplink and 20 GHz downlink using DPSK modulation. Some assumptions will have to be made in the link budget since some of the details of the system are classified. We will assume that the receive antenna has a gain of 48 dB, the system bandwidth is 70 MHz. Using DPSK, we see that we can supply a bit rate of 103.7 Mbs using 70MHz. We assume that the uplink and downlink antennas aboard the Milstar satellite have the same antenna gain. We also assume the LNAs used have a 3-dB noise figure. The uplink and downlink budgets are shown in the following tables.

Table 4.8 Military GEOSAT Uplink

Path Length	42,170,000 m
Center Frequency	44 GHz
Receiver Antenna Gain	48 dB
Transmit Power	103 W
Transmit Antenna Gain	45 dB
Off-boresight	-3 dB
Bit Rate	103.7 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-217.8 dB
Power Received	-109.7 dB
System Temperature	570 K
Bandwidth	70 MHz
Noise Power	-122.6 dB
C/N	12.9 dB
E_b/N_o	11.2 dB
Bit Error Rate (DPSK)	9.3996×10^{-7}

Table 4.9 Military GEOSAT Downlink

Path Length	42,170,000 m
Center Frequency	20 GHz
Receiver Antenna Gain	40 dB
Transmit Power	36.5 W
Transmit Antenna Gain	48 dB
Off-boresight	-3 dB
Bit Rate	103.7 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-211.0 dB
Power Received	-112.3 dB
System Temperature	310 K
Bandwidth	70 MHz
Noise Power	-125.2 dB
C/N	12.9 dB
E_b/N_o	11.2 dB
Bit Error Rate (DPSK)	9.7437×10^{-7}

4.10 Commercial GEOSAT Links

The commercial GEOSAT link budget will be calculated using specifications from the Intelsat IX system. More details of the Intelsat IX system can be found later in the thesis. Each Intelsat IX satellite will have a capacity of up to 96 units of 36 MHz each. The satellites will use 44 transponders in the C-band from 9 to 25 W and 12 transponders in the Ku-band from 40 to 60 W. The Intelsat IX transponders have EIRPs of 31 to 37 dBW in the C band, and 47 to 49 dBW in the Ku band [31] [32]. The GEOSAT link does not have liquid rain in the path to affect reliability. To minimize frequency conversion, we will use the Ku band transponders with 16 GHz uplink, and 12 GHz downlink. We will assume that the system uses QPSK modulation, the receive antenna aboard the satellite has a gain of 36 dB, and the uplink and downlink will each occupy two of the 36 MHz frequency units or 72 MHz. Using QPSK, we can provide 106.7 Mbs within a bandwidth of 72 MHz. In the downlink, knowing the transmit EIRP, we will solve for the UAV's receive antenna gain to achieve a BER of 1e-6. In the uplink, we will solve for the UAV transmitter EIRP to achieve a BER of 1e-6. The link budgets are shown in the following tables.

Table 4.10 Commercial GEOSAT Uplink

Path Length	42,170,000 m
Center Frequency	16 GHz
Receiver Antenna Gain	43 dB
Transmit Power	67.8 W
Transmit Antenna Gain	42 dB
Off-boresight	-3 dB
Bit Rate	106.7 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-209.0 dB
Power Received	-110.7 dB
System Temperature	510 K
Bandwidth	72 MHz
Noise Power	-123.0 dB
C/N	12.2 dB
E_b/N_o	10.5 dB
Bit Error Rate (QPSK)	9.9535×10^{-7}

Table 4.11 Commercial GEOSAT Downlink

Path Length	42,170,000 m
Center Frequency	12 GHz
Receiver Antenna Gain	50.44 dB
Transmit EIRP	48 W
Off-boresight	-3 dB
Bit Rate	106.7 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-206.5 dB
Power Received	-113.1 dB
System Temperature	295 K
Bandwidth	72 MHz
Noise Power	-125.3 dB
C/N	12.2 dB
E_b/N_o	10.5 dB
Bit Error Rate (QPSK)	9.8799×10^{-7}

4.11 Trunk Links

The trunk uplink and downlink will be used by the commercial system to link calls in and out of the UAV-LMDS system. In the commercial system, the ground station will be a gateway into the existing communications infrastructure. This link can also serve to carry command and control information to and from the UAV. For the commercial system, the ground station will be located directly underneath the UAV to minimize path length and rain attenuation. In the military system, this link can be used to link a base or headquarters to soldiers in the field. If battlefield conditions are such that a headquarters or control station cannot be set up underneath the UAV, command and control information can be sent remotely over a different link or through the GEOSAT link. The trunk uplink is intended to carry a large amount of data. We will try to minimize the demands of the UAV equipment and specify that the ground station has a high EIRP. We will also compare 64-QAM and 256-QAM in hopes that the link will support 256-QAM. Similar to the Hop link, using a 150 MHz bandwidth we can provide a bit rate of 666.67 Mbs with 64-QAM and 888.89 Mbs with 256-QAM. The link budgets (calculated for Blacksburg, Va.) are shown in the tables below.

Table 4.12 Trunk Uplink, 64-QAM

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	31.15 GHz
Receiver Antenna Gain	38 dB
Off-boresight	-3 dB
Transmit Power	29.9 W
Transmit Antenna Gain	42 dB
Bit Rate	666.67 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-147.2 dB
Percentage of time out due to excess rain	0.0016%
Rain Margin	36.9 dB
Power Received	-94.3 dB
System Temperature	570 K
Bandwidth	150 MHz
Noise Power	-119.3 dB
C/N	24.9 dB
E_b/N_o	18.5 dB
Bit Error Rate (64-QAM)	9.6846×10^{-7}

Instead of increasing the transmit power or antenna gains, we decrease the availability to achieve a link using 256-QAM operating with 1e-6 BER. We do this to avoid the large power demands of 256-QAM. With 64-QAM we had an availability of 99.9984%, but on the 256-QAM uplink, we will have a decreased availability of 99.99686%.

Table 4.13 Trunk Uplink, 256-QAM

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	31.15 GHz
Receiver Antenna Gain	38 dB
Off-boresight	-3 dB
Transmit Power	29.9 W
Transmit Antenna Gain	42 dB
Bit Rate	888.89 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-147.2 dB
Percentage of time out due to excess rain	0.0031%
Rain Margin	30.0 dB
Power Received	-87.5 dB
System Temperature	570 K
Bandwidth	150 MHz
Noise Power	-119.3 dB
C/N	31.8 dB
E_b/N_o	24.0 dB
Bit Error Rate (256-QAM)	9.9524×10^{-7}

The downlink is more forgiving because the ground station antenna will only see roughly 14° K of sky noise [30]. If possible, we would like to increase the availability of the link.

Table 4.14 Trunk Downlink , 64-QAM

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	31.15 GHz
Receiver Antenna Gain	42 dB
Off-boresight	-3 dB
Transmit Power	20.1 W
Transmit Antenna Gain	38 dB
Bit Rate	666.67 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-147.2 dB
Percentage of time out due to excess rain	0.00151 %
Rain Margin	37.9 dB
Power Received	-97.1 dB
System Temperature	304 K
Bandwidth	150 MHz
Noise Power	-122.0 dB
C/N	24.9 dB
E_b/N_o	18.5 dB
Bit Error Rate (64-QAM)	9.8322×10^{-7}

Table 4.15 Trunk Downlink, 256-QAM

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	31.15 GHz
Receiver Antenna Gain	42 dB
Off-boresight	-3 dB
Transmit Power	20.1 W
Transmit Antenna Gain	38 dB
Bit Rate	888.89 Mbs
Implementation Margin	2 dB
Free Space Attenuation	-147.2 dB
Percentage of time out due to excess rain	0.00284 %
Rain Margin	31.0 dB
Power Received	-90.2 dB
System Temperature	304 K
Bandwidth	150 MHz
Noise Power	-122.0 dB
C/N	31.8 dB
E_b/N_o	24.0 dB
Bit Error Rate (256-QAM)	1.0030×10^{-6}

Like the UAV hop link, the trunk down and uplink can be made using both 64-QAM and 256-QAM. The difference between the two modulation schemes shown here is only in the rain availability. The final choice between the two modulations will depend on the necessary bit rate, availability and implementation issues. As stated in the UAV-hop link section, more complicated communications equipment is needed to support the more aggressive modulation scheme.

4.12 Link Summary

In the preceding link budgets, the main goal was to achieve a BER of 10^{-6} using as little power and the lowest antenna gains as possible. The above link budgets should be used as a guide for design; if system specifications change, the parameters of the link can be recalculated. When a link needs to be changed in any way, for example implemented with a greater bit rate or within a smaller bandwidth, we only need to turn to the following equation to understand what the results of the change will be:

$$\frac{E_b}{N_o} = \frac{C}{N} * \frac{B}{R_b}$$

By lowering the EIRP or receive antenna gain, we will lower E_b/N_o which will increase the BER. Raising the bit rate of the link will likewise decrease the E_b/N_o. The engineering principle of tradeoffs applies; “you can’t get something for nothing.”

Chapter 5 System Design

The system design for the UAV-LMDS system will be broken into two main sections. The orbit design and the ground design. The orbit section will discuss the aspects of the UAV and GEOSAT components of the UAV-LMDS system, including antenna design, and communication payload design. The ground section will include a system-level user transceiver design, antenna discussions, and other issues.

5.1 Orbit

5.1.1 UAV

The UAV plays the central role in the UAV-LMDS system. Acting as a hub, the UAV makes this system unique and could represent a new trend in communications providing. One of the most important considerations that will be made in the design concerns the weight and aerodynamic properties of the payload.

5.1.1.1 Downlink Antennas

The UAV antenna design is a unique element of the UAV-LMDS system. For this reason, two detailed designs will be presented and compared here. Wire dipole antenna arrays and an arrangement of pyramidal horns will be compared. Our goal is to design the UAV downlink antennas so that multiple beams can be present on the ground for frequency reuse, support a wide bandwidth, and also concentrate radiated power downward. We also will design for low sidelobes to minimize co-channel interference between cells. As the UAV will be circling above the service area, some provision must be made so that the beams will remain stationary on the ground. If the beams are kept stationary, user handoff issues can be avoided. Turbulence and winds will also have a destabilizing effect on the UAV and we will attempt to counteract these effects.

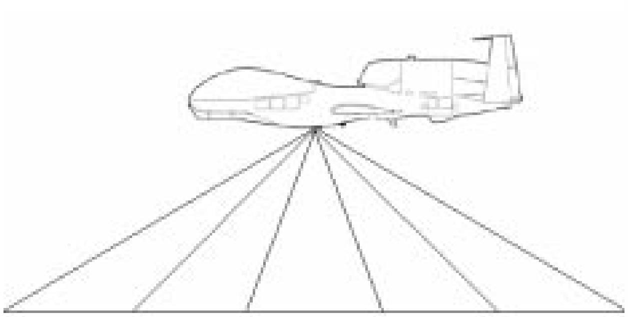

Figure 5.1 Downlink Beam Cross-section

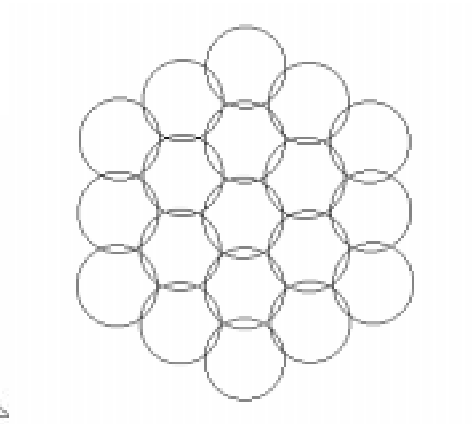

Figure 5.2 Downlink Beam Footprint

5.1.1.1.1 Arrays

We will first present 2-dimensional array designs of uniformly spaced, non-uniformly excited and linear phased dipoles. This array will be non-uniformly excited to minimize the side lobe level (SLL). These antenna array beams can be scanned electronically to compensate for UAV movement and keep the beams stationary at the ground. Looking at the above figure, the reader will notice that there are essentially three different beams and thus only three arrays need to be designed, those for the center beam, the middle beams, and the perimeter beams.

All three types of antenna arrays will have a 2-dimensional arrangement of half-wave dipoles with a conducting ground plane mounted above them to eliminate upward radiation and increase gain. The array orientation is shown in the below figure.

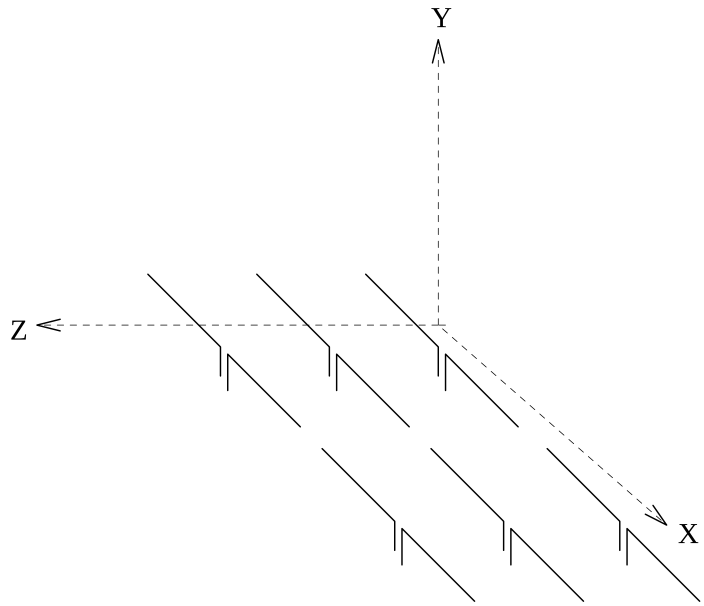

Figure 5.3 Antenna Array Orientation

The antenna arrays have the following characteristics and principal plane patterns:

Table 5.1 Center Beam Antenna Array Characteristics (1 center beam total)

Number of elements in X direction	3
Number of elements in Z direction	3
Total number of elements	9
m, X direction	2
N, X direction	2
M, Z direction	2
N, Z direction	2
ψ_{1x} [rad]	-1.9
ψ_{2x} [rad]	1.9
ψ_{1z} [rad]	-1.2
ψ_{2z} [rad]	1.2
HPBW XY-plane [deg]	74
HPBW YZ-plane [deg]	76
Directivity [dB]	8.592
Side Lobe Level [dB]	$-\infty$
Distance between elements, X direction	0.002
Distance between elements, Z direction	0.0032

Table 5.2 Middle Beam Antenna Array Characteristics (6 middle beams total)

Number of elements in X direction	9
Number of elements in Z direction	9
Total number of elements	81
M, X direction	4
N, X direction	3
M, Z direction	4
n, Z direction	3
ψ_{1x} [rad]	-2
ψ_{2x} [rad]	2
ψ_{1z} [rad]	-2
ψ_{2z} [rad]	2
HPBW XY-plane [deg]	30°
HPBW YZ-plane [deg]	28°
Directivity [dB]	13.6291
Side Lobe Level [dB]	$-\infty$
Distance between elements, X direction	0.0034 m
Distance between elements, Z direction	0.0034 m

Table 5.3 Perimeter Beam Antenna Array Characteristics (12 perimeter beams total)

Number of elements in X direction	25
Number of elements in Z direction	25
Total number of elements	625
m, X direction	4
n, X direction	7
m, Z direction	4
n, Z direction	7
ψ_{1x} [rad]	-2.6
ψ_{2x} [rad]	2.6
ψ_{1z} [rad]	-2.6
ψ_{2z} [rad]	2.6
HPBW XY-plane [deg]	10°
HPBW YZ-plane [deg]	10°
Directivity [dB]	18.730
Side Lobe Level [dB]	-50.6
Distance between elements, X direction	0.0044 m
Distance between elements, Z direction	0.0044 m

5.1.1.1.2 Horns

The second design presented here is of an arrangement of pyramidal horn antennas. We will compare the pyramidal horn designs to the array designs and then choose between the two. These pyramidal horns will be arranged such that as the UAV changes position, the onboard electronics will be able to switch between horns to maintain stationary coverage on the ground. The horn arrangement will have a convex shape shown below in Figure 5.3, and will be mounted inside the UAV in the bulge in the bottom of the fuselage.

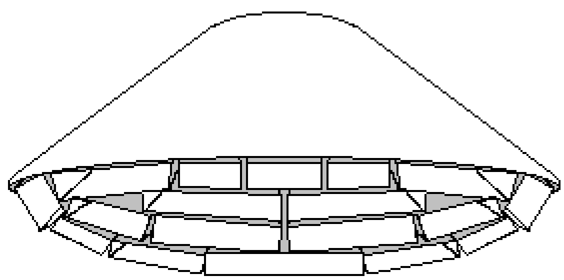

Figure 5.4 Pyramidal Horn Arrangement

The coverage area will still be divided into 19 equal beams, but the pyramidal horn arrangement will carry 37 horns. The horn arrangement will be controlled and driven in one-dimension to compensate for the UAVs rotations about the roll axis, see Figure 5.4. Therefore, the horn arrangement will act like a pendulum; always pointing to the center of the earth, and remaining horizontal. However, as the UAV rotates about the yaw axis the antennas will need to be switched to compensate for this rotation.

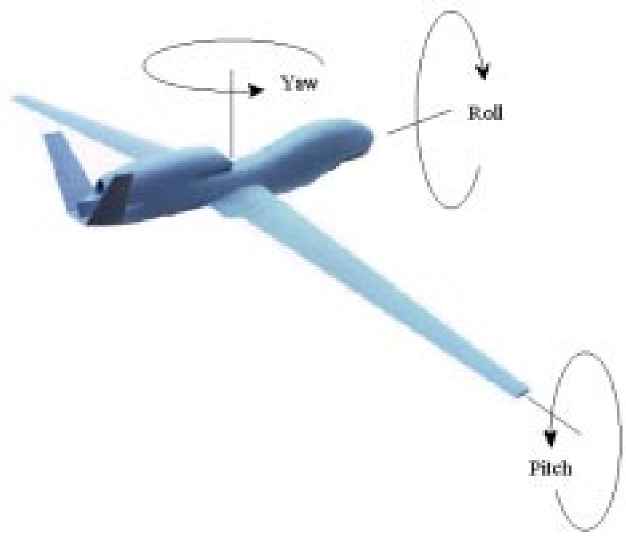

Figure 5.5 Roll, Pitch and Yaw Illustration

Essentially, there needs to be only 19 antennas present to cover the entire region, but for all beams except the center beam, there will be an intermediate horn to fill in coverage as the UAV turns. No intermediate beam is needed for the center beam as it remains stationary. This built-in feature of the downlink pyramidal horns allows the UAV-LMDS system to maintain fixed beam patterns on the ground. The 37 (19 + (19-1)) beams are shown below in Figure 5.5.

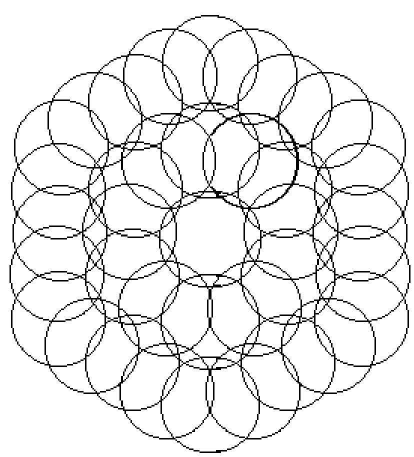

Figure 5.6 Horn Arrangement Downlink Pattern

As with the antenna arrays, there are essentially only three different types of antennas, the center beam, the middle beams and the perimeter beams. The three designs are tabulated below:

Table 5.4 Center Beam Pyramidal Horn Characteristics (1 beam total)

HPBW	73.475°
G	4.8161 (6.8 dB)
a	0.007112 m
b	0.003556 m
A	0.0106 m
B	0.0082 m
R_1	0.0035 m
R_2	0.0031 m
l_h	0.0063 m
l_e	0.0051 m
R_H	0.0011 m
R_E	0.0017 m
S	0.2500
T	0.3750

Table 5.5 Middle Beam Pyramidal Horn Characteristics (12 middle horns total)

HPBW	23.199°
G	48.6447 (16 dB)
a	0.007112 m
b	0.003556 m
A	0.0334 m
B	0.0260 m
R_1	0.0349 m
R_2	0.0316 m
l_h	0.0387 m
l_e	0.0341 m
R_H	0.0275 m
R_E	0.0272 m
s	0.2500
t	0.3750

Table 5.6 Perimeter Pyramidal Horn Characteristics (24 perimeter beams total)

HPBW	9.065°
G	316.4009 (25 dB)
a	0.007112 m
b	0.003556 m
A	0.0840 m
B	0.0674 m
R_1	0.2197 m
R_2	0.2123 m
l_h	0.2237 m
l_e	0.2149 m
R_H	0.2011 m
R_E	0.2011 m
S	0.2500
T	0.3750

(See Appendix for downlink horn radiation patterns)

Comparing the largest diameter that this horn antenna arrangement can have to the fuselage dimensions, we discover that it will fit with room to spare. The arrangement is only 9.7 in wide, while the fuselage is 4.8 ft wide.

5.1.1.1.3 Antenna Design Comparison

Each antenna design has been created to conform to the same specifications. However, there are several issues that need to be considered in making a final choice for the design. When dealing with antenna arrays, one must always consider how to feed each element of the array. The more elements and the higher the frequency used, the more difficult it is to implement the array. The antenna array perimeter beams pose the biggest problem, with 625 elements each to create a 10° x 10° beam. The feed networks needed to feed 12 of these 625 element arrays are a monumental obstacle. Aside from being an implementation obstacle, these feed networks would add a considerable amount of weight to the communications payload.

Looking at industry's techniques, pyramidal horns can be injection molded in plastic. The interior of the horn is then painted with a coating of NiCu [44]. This manufacturing technique lowers the weight and cost of each pyramidal horn. The horn arrangement is simple, small and the feeds can simply be switched as the UAV changes position. Therefore, we will choose the horn arrangement to serve as our downlink antenna.

5.1.1.1.4 Downlink Beam Switching

The pyramidal horns are designed to compensate for aircraft motion and maintain fixed beams on the ground. The horns are allowed to pivot to compensate for rotations about the roll axis. But as the aircraft pivots about the yaw axis, the beams must be switched between the horns. The aircraft will need accurate on-board navigation equipment, possibly including Global Positioning System (GPS) navigation, to determine its exact position and heading. This navigation information will be fed to a control system that will switch the downlink antenna beams as the UAV circles.

5.1.1.2 UAV Uplink antennas

The uplink antenna onboard the UAV needs only to have one beam. Since the UAV will look like a single point to the users on the ground, no frequency reuse can be implemented. Instead of having a very large beam with a beamwidth of 150° and a very low gain, we will design several beams to increase the gain of the uplink antenna.

Increasing the gain of the uplink antennas will allow the user transceivers to be less expensive and heavy because a lower transmit power is necessary. Also, increasing the gain of the uplink antennas means that the user antennas can have lower gain antennas. A user directly beneath the UAV will have a better link than the user at the perimeter of coverage. This is mainly due to the larger amount of potential rain attenuation that the perimeter user will face. Our goal is to have a 1 W transmit power for all user transmitters.

Considering the functionality and other benefits of the pyramidal horn arrangement design, we will design the uplink antennas to be the same. From the uplink budgets we found that an uplink antenna gain of 24 dB was suitable. Using this specification and equation (3.29), we find that each of the beams has a beamwidth of roughly 10°. We discover that roughly 225 of these 10° beams are needed to serve the entire coverage area. The uplink antennas have the following characteristics shown in the table below.

Table 5.7 Uplink Pyramidal Horn Characteristics (roughly 225 beams total)

$HPBW_E$	9.6462°
$HPBW_H$	11.1407°
G	24 dB
a	0.007112 m
b	0.003556 m
A	0.0750 m
B	0.0600 m
R_1	0.1751 m
R_2	0.1679 m
l_h	0.1790 m
l_e	0.1705 m
R_H	0.1585 m
R_E	0.1579 m
S	0.2500
T	0.3750

Each horn antenna has a volume of 262e-6 m^3 and there should not be a problem in fitting them in the fuselage of the UAV.

(See Appendix for uplink horn radiation patterns)

5.1.1.3 Other UAV antennas

There are other antennas on board the UAV whose detailed designs will not be presented here. These antennas include the UAV hop antennas, GEOSAT link antenna and trunk-uplink and downlink antennas. The UAV hop antennas transmit and receive calls that need to hop between UAVs that are in sight. The GEOSAT link antenna transmits and receives calls to a GEOSAT for transfer to other UAVs that are out of sight from the originating UAV. The trunk-uplink and trunk-downlink antennas link UAVs in the public system to the existing terrestrial communications infrastructure, allowing calls to be made into and out of the UAV-LMDS system. The trunk-uplink and trunk-downlink can also be used by the military for command and control of the UAV or for receiving large amounts of information to a central point like a headquarters. In the link section we determined link parameters like path length and required SNR, and we specified the antenna gains and transmitter powers for these antennas.

5.1.1.4 UAV Communications Payload

The UAV-LMDS system is intended to handle roughly 940 simultaneous users. Looking at terrestrial equipment that is on the market now, hub units are relatively small in size, suitable for the limited payload of an aircraft. Because the UAV is not subject to radiation, inexpensive, non-radiation-hard equipment can be used for the communications payload. This is another advantage that UAVs have over an all-satellite constellation. The central part of the UAV communications payload is the router. The router reads the addressing information attached to each data packet and directs the packet to one of four destinations. If the intended recipient is serviced by the UAV, the data is simply directed to the proper downlink antenna and sent. The second scenario occurs when the intended user is serviced by an adjacent UAV. In this case the router would determine that the intended recipient is not one of its own and then the data packet will be re-modulated using a more aggressive modulation scheme and sent out to the adjacent UAV. If the call must hop over several UAVs to reach the recipient, then this process will be repeated until the destination UAV is reached. Once the call reaches the destination UAV, the data packet will be re-modulated and then sent down to the recipient.

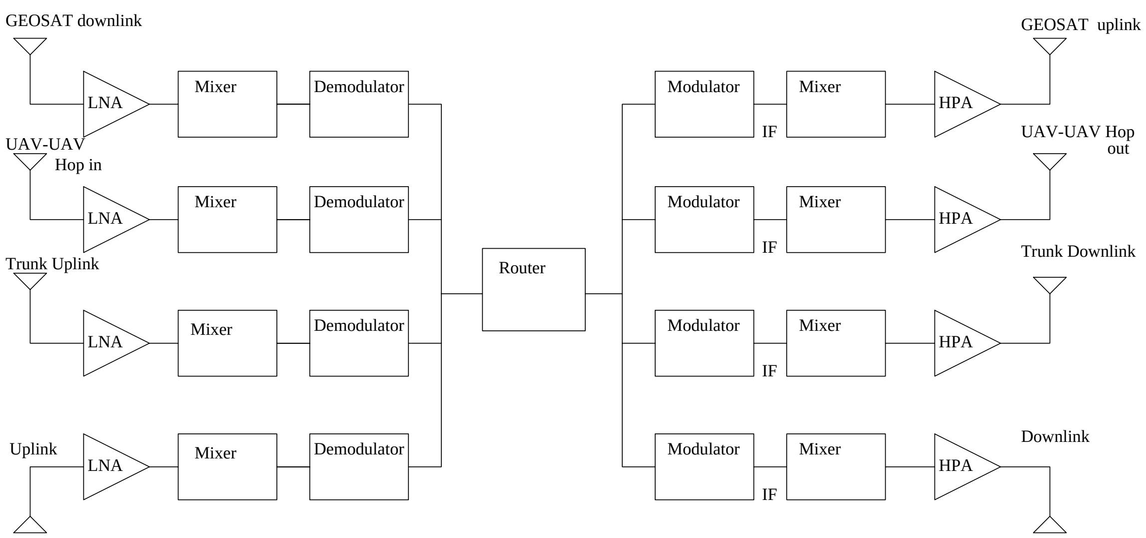

Figure 5.7 Global Hawk Communication Payload

Depending upon what GEOSAT the UAV-LMDS system uses, the UAV will need to carry a payload to properly communicate with it. GEOSAT systems will be discussed in the next section.

5.1.2 GEOSAT

The geostationary satellite link is very important to making the UAV-LMDS system truly global. When a call cannot hop between two UAVs that are in sight of one another, the call must be carried over a GEOSAT link. This system design will not encompass the design of an entire GEOSAT, but we have assumed that the private or military UAV-LMDS system will be able to lease or use links on an existing GEOSAT. A GEO satellite's high altitude leads to high transmission delays, or latency. However, maximum delay between UAVs on opposite ends of the earth, neglecting atmospheric delays, would only be 0.284s.

The UAV-LMDS system could require a completely new GEOSAT network to support its novel services. However, it is beneficial to study existing and upcoming GEOSATs to get an idea of the types of capabilities available. Possible satellite service providers are Intelsat, PanAmSat and the Hughes Spaceway system. PanAmSat operates 19 satellites and can offer a data throughput of 48Mbps. Intelsat manages several classes of satellites that serve to link communications globally. Intelsat IX is being built by Space Systems Loral and is intended to replace the INTELSAT VI series. Due to be launched in 2004, the Intelsat IX series of geostationary satellites is designed to deliver broadband services, including high-data rate trunking [33]. The Intelsat IX system consists of 4 satellites costing approximately $1 billion and is touted as offering a quality of service comparable to fiber cables. Because the system has yet to be completed, many of the details of the Intelsat IX series are changing, but link budgets will be done using published information.

The information regarding the GEOSATs that is crucial to the UAV-LMDS design is antenna gains, modulation, frequencies used, and bandwidth supported. With this information, we can determine the amount of data that can be transported through the satellite link and what antenna gains and transmitted power are needed.

The military system could utilize a commercial satellite or the Military, Strategic, and Tactical Relay Satellite (Milstar). The Milstar program is a $17.3 billion communication program designed to provide secure worldwide wartime telecommunications. The Milstar constellation consists of 6 satellites in geostationary orbit. Milstar uses EHF and UHF frequencies and has inter-satellite links at 60 GHz, which is absorbed by the atmosphere and is inaccessible to receivers on the ground [34] [35].

The Milstar constellation was designed for cold-war conflict and survival in a hostile space environment. The second series of Milstar satellites, the block 2 satellites, would be applicable to the UAV-LMDS system. The block 2 spacecraft carry a low data rate (LDR) payload which operates at 75 bps - 2400 bps and a medium data rate (MDR) payload operating at 4800 bps to 1.544 Mbps per channel. With 32 channels operating at 1.544 Mbps, the Milstar block 2 satellites could be reconfigured to carry UAV-LMDS traffic [36].

The medium data rate payload aboard Mistar that we are interested in operates at a 44 GHz uplink and a 20 GHz downlink and uses differential phase shift keying (DPSK) modulation. To minimize enemy detection and thwart jamming, the MDR uses very narrow spot beams for up and downlinks. To further enhance security, uplink and downlink transmissions are frequency hopped. Milstar satellites carry solar panels which provide 8000 W [36] [37].

5.2 Ground

5.2.1 Military Ground

The military users of the UAV-LMDS system will be individual soldiers, and vehicles, including tanks, ships and personnel carriers. For this reason, the military ground terminal needs to be compact and robust. While there are a multitude of commercial products available, military uses demand higher standards. The military ground unit will be designed for the individual soldier and this design can be easily adapted to larger, vehicular applications.

The major obstacles in the design of a ground terminal for individual use are weight and bulk. While engaging in battle, a soldier does not need to carry unnecessary weight or become a larger target. Currently, individual use communications terminals like Single Channel Ground Airborne Radio System (SINCGARS) are using up to 5 W [39]. To keep weight and cost down, the military transceiver will have an operating power of 1 W or less.

5.2.1.1 Antenna

Continuing with the theme of small size and lightweight, the soldier carried antenna will be a horn because of its beneficial size characteristics. The antenna can be mounted on a backpack and should have a beamwidth that is of adequate size to allow a soldier to communicate while standing or crouching. This antenna will be used for transmitting and receiving.

5.2.1.2 RF Block Diagram

Shown below are the block diagrams for the military transceiver.

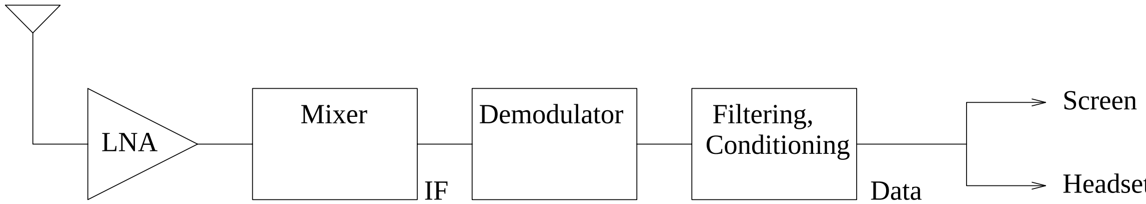

Figure 5.8 Military Receiver

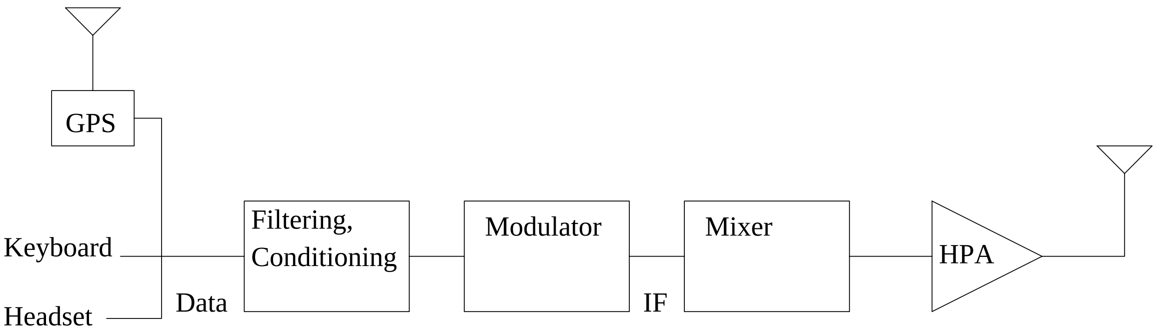

Figure 5.9 Military Transmitter

5.2.2 Commercial Ground

Commercial users of the UAV-LMDS system will be fixed, operating from buildings such as homes or offices. The customer premise equipment (CPE) will consist of a modem, transceiver and a roof-mounted antenna. The modem will interface with a personal computer, where the multimedia services delivered by LMDS will be utilized. These pieces of equipment are readily available on the new marketplace that is exploding to support LMDS ventures.

5.2.2.1 Antennas

The roof-mounted subscriber antenna will need to be pointed in the UAV's direction without intermediate vegetation or obstacles. With a typical antenna gain of 36 dBi, the subscriber antenna's 3 dB beamwidth is roughly 26°. At 60,000 ft, the coverage area is 602 810 174 ft^2, (diameter of 27704 ft). This coverage area should allow the subscriber antenna to "see" the UAV while it circles overhead, since the UAV would have to keep within a 14000 ft circling radius. The typical LMDS subscriber antenna is a 12" parabolic dish with a radome, an example is shown below.

Figure 5.10 Customer Premise Equipment

5.2.2.2 RF Block Diagram

The commercial RF block diagrams are very similar to the military diagrams.

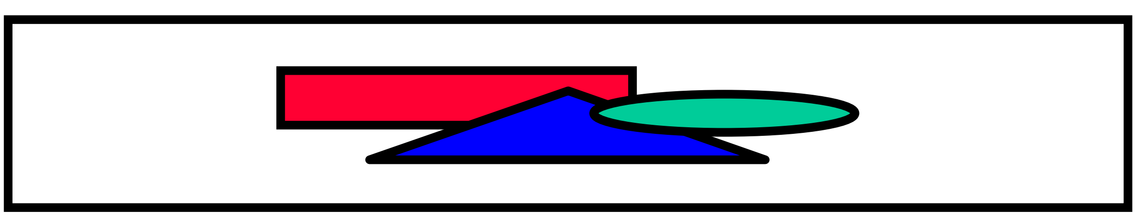

Figure 5.11 Commercial Transmitter

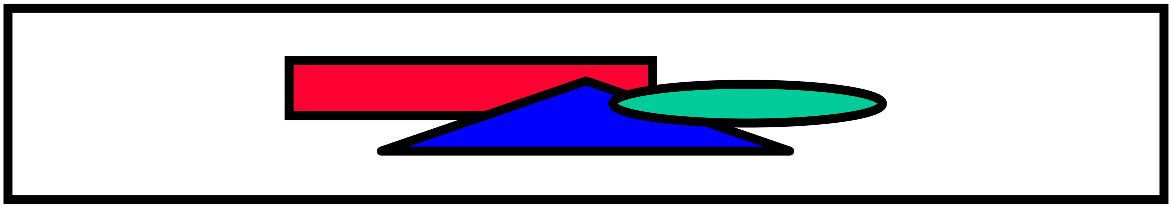

Figure 5.12 Commercial Receiver

Chapter 6 Implementation Issues

6.1 Co-channel Interference

When designing a system with frequency reuse, it is important to investigate how beams using the same frequency interfere with each other. To perform this analysis we examine the frequency reuse pattern to determine the cells that would interfere with one another. Knowing the interfering cells, we can than calculate a link budget using antenna patterns to determine the off-boresight attenuation. The graphic below shows the interference paths that we will analyze. Because of the repetitive nature of the frequency reuse pattern, these three interference paths are repeated throughout the downlink.

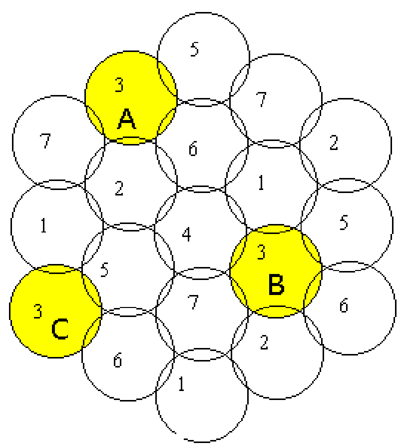

Figure 6.1 UAV-LMDS Frequency Reuse Pattern and Interfering Beams

To calculate the co-channel interference we find the direction and angle from boresight of the interference path and determine the decreased antenna gain in that direction. This decreased in antenna gain is determined from the antenna patterns and is subtracted from the antenna gain in the link budget. Since the interference path is almost the exact path as the wanted signal path, we include rain attenuation in the link budget. The interference link equation is shown below:

$$P_I = P_{It} + G_r + G_t - OffAxisGain - PathLoss - RainAttenuation$$

We then compare the total amount of interference to the amount of noise power received and determine the effect.

Table 6.1 Co-channel Interference Paths

Interference Path	**Path Length [m]**	**Antenna Gain /off-axis gain**	**Received Interference Power [dBW]**
B to A	57,600	16 dB / -30 dB	-139.0
C to A	57,600	25 dB / -40 dB	-140.0
A to C	57,000	25 dB / -40 dB	-140.0
B to C	57,600	16 dB / -30 dB	-139.0
A to B	24,200	25 dB / -40 dB	-131.5
C to B	24,200	25 dB / -30 dB	-131.5

Now we must find the total power received at each site, A, B, and C. We compare this power to the noise power calculated in the downlink budgets.

Table 6.2 Co-Channel Interference Powers

Site	**Total Co-channel Interference [dBW]**	**Calculated Noise power [dBW]**	**Total Unwanted Power [dBW]**	**Difference between Calculated and Total Unwanted Power [dBW]**
A	-136.5	-126.6277	-126.2	0.4
B	-128.5	-126.6911	-124.5	2.2
C	-136.5	-126.6277	-126.2	0.4

The total amount of unwanted signal power or “noise” that the co-channels add to the downlinks is significant. In heavy rain conditions, this increase in unwanted signal will increase the BER per link. For example, co-channel interference causes the BER of the site B downlink to increase to 1.6232×10^{-4}.

If we consider the effect of this co-channel interference on the link in clear air situations, we find that there is plenty of margin designed into the link to compensate for the interference. For example, in clear air conditions with the added co-channel interference, the BER of the site B downlink increases to 3.4256×10^{-9}. This BER is still lower than our goal BER of 10^{-6}.

6.2 Mobility

LMDS has been developed for fixed terrestrial communications. The relatively small beamwidths of the UAV-LMDS system and propagation characteristics of the frequencies present difficulties to mobile users like soldiers in battle. The military UAV-LMDS system will need to compensate for this movement. There are several characteristics and elements to the UAV-LMDS system that will allow the system to support limited movement. Fast moving vehicles like airplanes will not be supported whereas soldiers and vehicles like tanks, jeeps and slow moving boats will be able to use the system. Transmissions will typically be bursty short messages like voice transmissions and GPS coordinates. Integrating GPS into the system will also allow the UAV to know where users are located and send transmissions in the appropriate downlink beam to compensate for movement. Another attribute of the UAV-LMDS system that simplifies the movement of the soldiers is the fact that the UAV and users know the general direction of each other; the UAV is up and the users are down. This simple fact eliminates degrees of freedom in knowing where transmissions should be directed or where they are coming from.

6.3 Vegetation Losses

Vegetation in the propagation path is very degrading to signals at LMDS frequencies and could be a concern. Typically, the US Navy operates on water and the

Marines normally stay near shorelines. Even though the UAV-LMDS military system will be used in amphibious situations, it is still important to analyze the effects of vegetation upon the link. There has been much research into the effects of vegetation upon millimeter wavelength signals. Losses depend upon characteristics of the vegetation like dielectric constant, density, physical size and shape [40]. Vegetative losses increase with the number of trees in the path and manifest themselves as attenuation, scattering and random polarization. Losses gradually taper off, shown in the below graph taken from [40]. This tapering has been explained as random polarization having less of an impact on total losses. The main loss mechanisms become attenuation and scattering. Beginning at about 3-4 trees, polarization losses begin to counteract themselves. The signal's polarization is changed from the undesired polarization to the desired one, and vice versa.

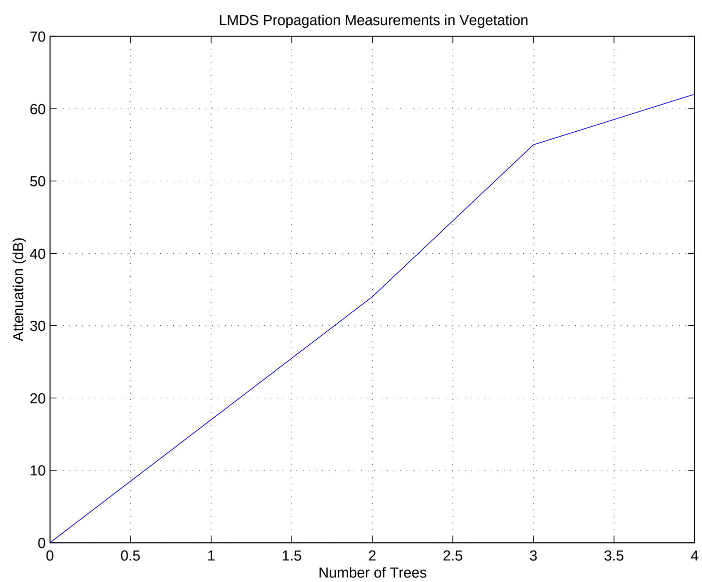

Figure 6.2 Vegetation Losses as a function of Number of Trees in the Propagation Path

According to a study done by Edward Manning vegetative fading is "almost certainly not due to incoherent propagation" [40]. As a signal passes through trees it is attenuated, scattered and becomes randomly polarized. It was also concluded that vegetative fading could be overcome by increasing transmitter EIRP. Depolarization would be a critical issue in a system using polarization diversity.

We can consider that if a soldier were in a forest, s/he would be sending and receiving through the equivalent of two trees in Manning's study. Vegetation attenuation depends on density and type of vegetation. Using experimental data from [40], we will analyze the effect of coniferous trees upon the uplink and downlink. Two trees in the propagation path introduce 34 dB of loss.

When two trees are added to the propagation path of a user on the perimeter of coverage, the uplink is disabled and cannot operate with an acceptable BER in clear air (no rain). To complete this perimeter link, the transmitter EIRP would have to be increased from 36 dB to 49.4 dB to achieve a BER of 10^{-6} in clear air. Assuming a constant antenna gain, transmitter power would have to jump from 1 W to 21.88 W. Using the original EIRP of 36 dB with vegetation and no rain, the uplink cannot maintain a BER if 10^{-6} even when users have an elevation angle of 90° (nadir point). To achieve a BER of 10^{-6}, the users' EIRP would have to be increased from 36 dB to 38.1 dB. If we again assume that antenna gain remains constant, the transmitter power would have to increase by 0.63 W. The link budget for a user at the nadir point is shown below.

Table 6.3 Uplink Link Budget, with 2 trees, clear air, using original 36 dB EIRP

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	28 GHz
Receiver Antenna Gain	24 dB
Off-boresight	-3 dB
Transmit Power	1.63 W
Transmit Antenna Gain	36 dB
Bit Rate	1.54 Mbs
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-146.3 dB
Vegetation Attenuation	-34 dB
Power Received	-124.2 dB
System Temperature	580 K
Bandwidth	519.75 kHz
Noise Power	-143.8 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	1.0134×10^{-6}

Vegetation severely disables the uplink and the downlink is similarly affected. To create a downlink that provides service to the nadir point user shown in the above uplink analysis, the UAV's transmit EIRP would have to increase from 20.8 dB to 43.3 dB. This clear weather link budget is shown in the below table.

Table 6.4 Downlink User serviced by center beam, 2 trees, clear air

UAV altitude	18,300 m (60,000 ft)
Path Length	17,600 m
Elevation Angle	90°
Center Frequency	28 GHz
Receiver Antenna Gain	36 dB
Transmit Power	68 W
Transmit Antenna Gain	36 dB
Off-boresight	-3 dB
Bit Rate	2.5 Mbs (135.24 Mbs)
Implementation Margin	1 dB
Clear Air Loss	2 dB
Free Space Attenuation	-146.3 dB
Vegetation Attenuation	-34 dB
Power Received	-107.0 dB
System Temperature	345 K
Bandwidth	861.207 kHz (45.6 MHz)
Noise Power	-126.6 dB
C/N	19.6 dB
E_b/N_o	14.9 dB
Bit Error Rate (16-QAM)	9.4545×10^{-7}

Considering the above link budgets, we can see that LMDS signals do not fare well in rain and vegetation. The above analyses attempted to change as little as possible of the original system parameters to demonstrate the system's reduced capacity as conditions worsened. As stated before, rain and vegetation losses can be overcome by increasing transmitter EIRP.

Chapter 7 Discussion and Conclusions

7.1 Discussion

This thesis shows that a viable communications system can be created using LMDS and UAVs. This system is truly dual-use, it can be used in a military environment or for public use. The use of LMDS in an aerial configuration is a new concept illustrated here. The large bandwidth of LMDS allows the system to support many uses at a large bit rate. The use of LMDS also has specific advantages to military users. The quickly attenuating signals and the high-gain antennas make the signals used in the system hard to intercept by enemies. The integration of GPS into the military UAV-LMDS system will aid soldiers, reduce friendly fire casualties and increase lethality. Another unique concept herein is the downlink antenna horn arrangement. This innovative antenna arrangement supplies adequate coverage in a small unit with a minimum of complexity.

7.2 Conclusions

This thesis presented a system design and analysis. This system can be used for military and civilian use and cases are presented for the demand for each. Included in the thesis are, background information on LMDS, UAVs and Geostationary satellites, and regulatory information. Also presented was information about competitive systems in the commercial arena, financial comparisons and information on commercial demand. After discussing communication theory and doing detailed link budgets, a system design was presented. This design included information pertaining to the military system and the private system. Also included were hardware discussions and antenna designs.

Following the design and implementation issues, issues like co-channel interference, mobility and vegetation were addressed. Using UAVs and LMDS, a viable, broadband, wireless communications system can be created for military and commercial use.

Appendix:

The following figures show the *E* and *H*-plane normalized radiation patterns for the three types of downlink pyramidal horns aboard the UAV.

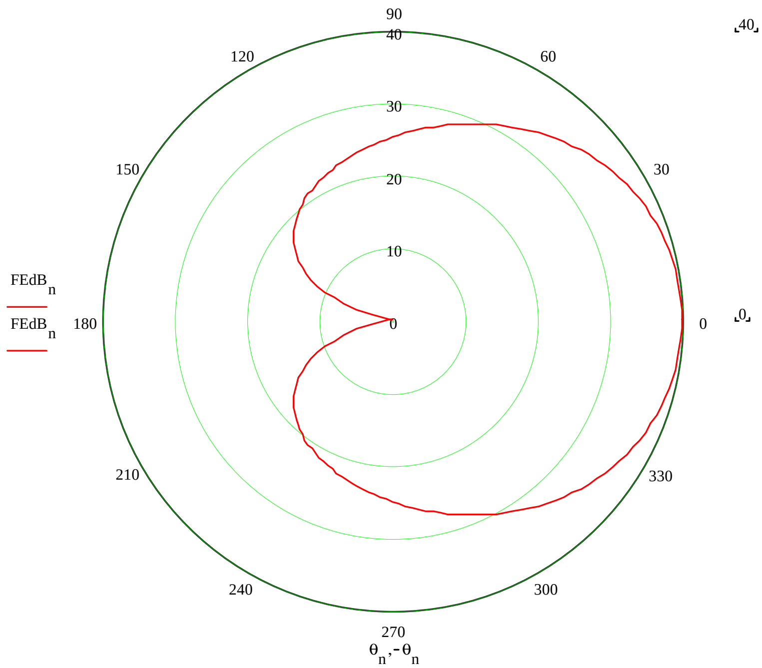

Figure A.1 Downlink Horn Center Beam, Total Pattern in YZ plane (*E*-plane)

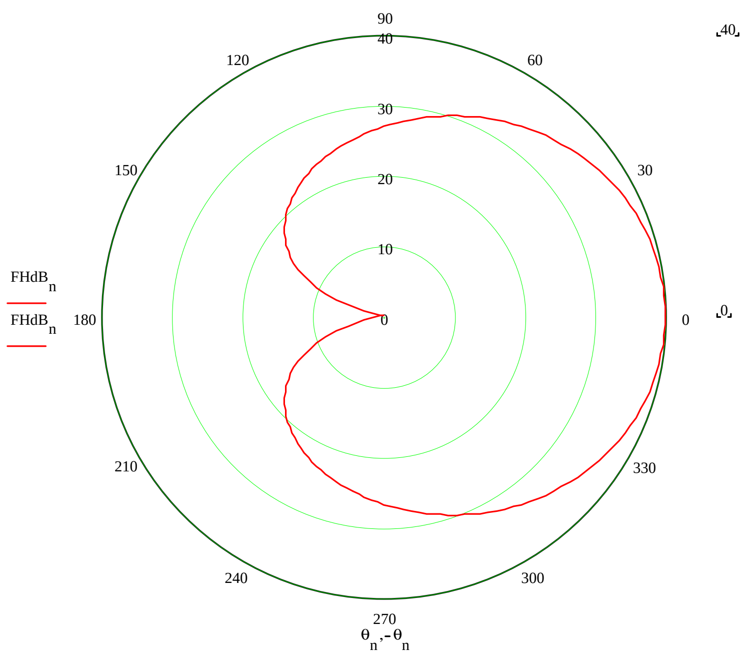

Figure A.2 Downlink Horn Center Beam, Total Pattern in XZ plane (*H*-plane)

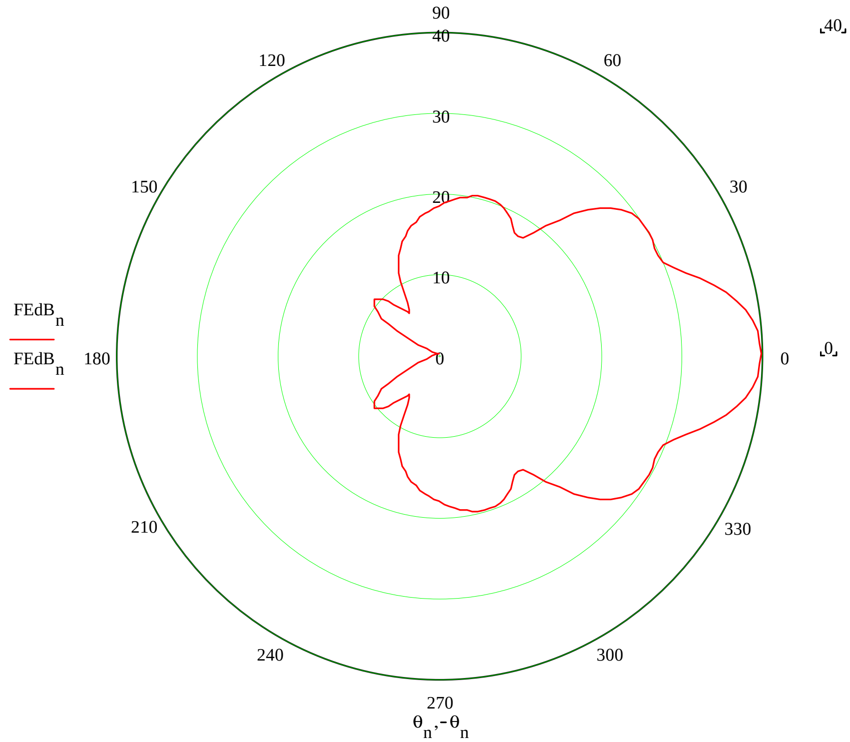

Figure A.3 Downlink Horn Middle Beam, Total Pattern in YZ plane (*E*-plane)

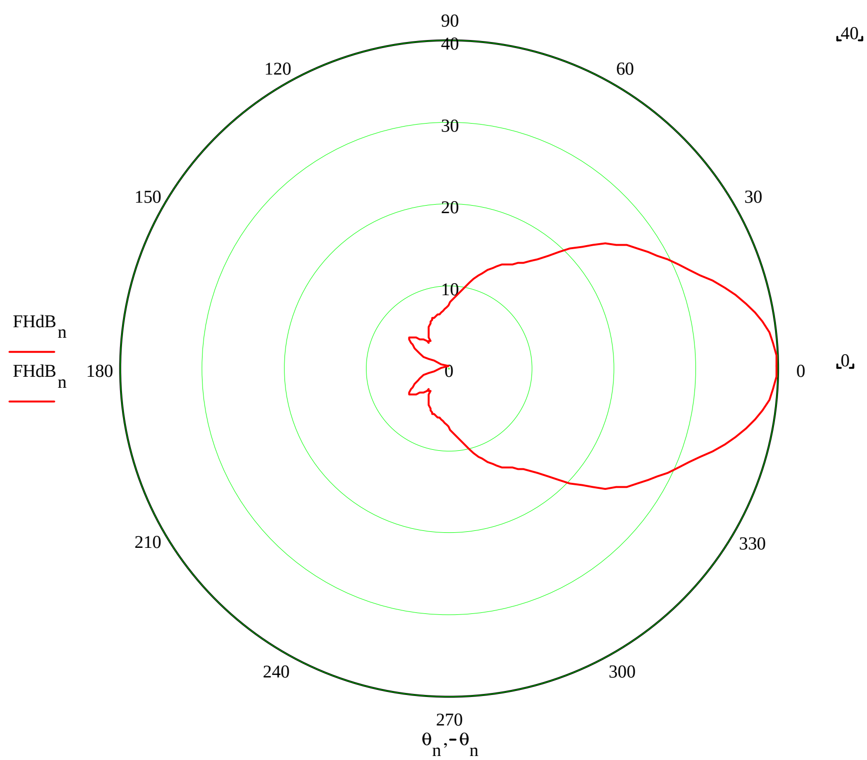

Figure A.4 Downlink Horn Middle Beam, Total Pattern in XZ plane (*H*-plane)

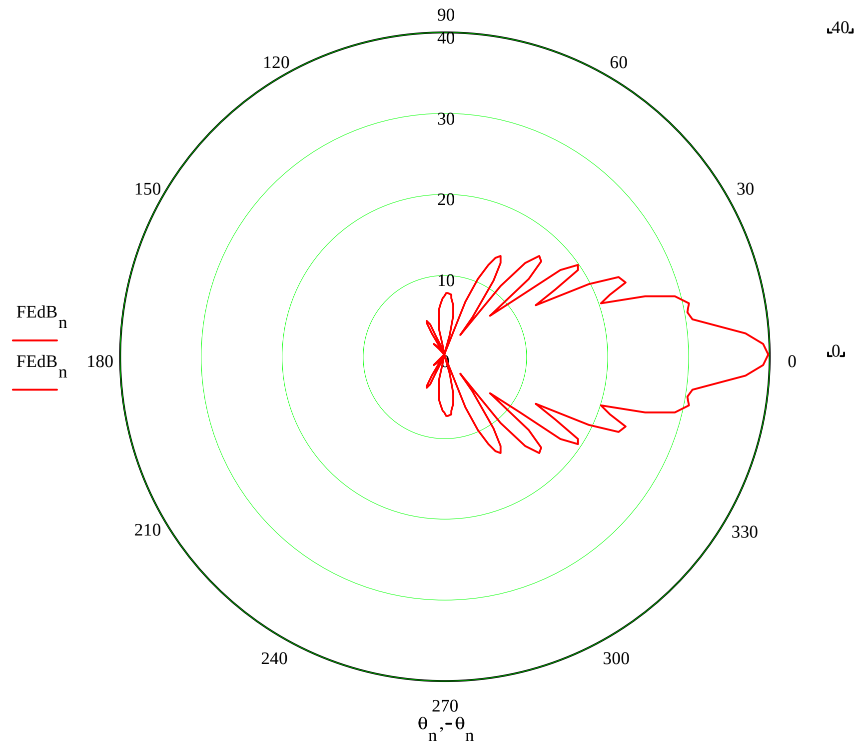

Figure A.5 Downlink Horn Perimeter Beam, Total Pattern in YZ plane (*E*-plane)

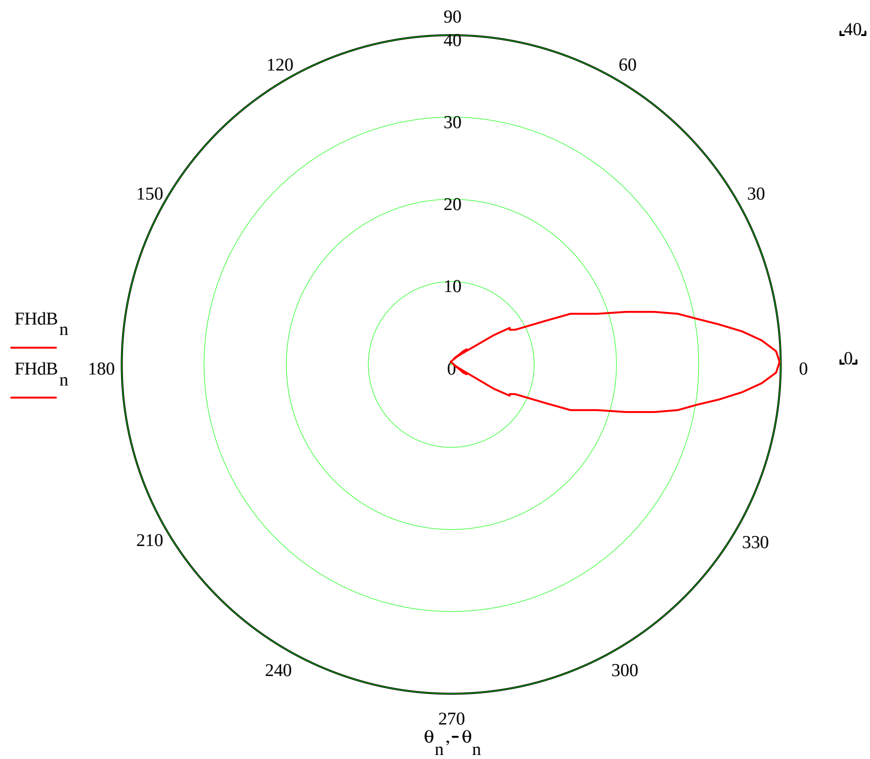

Figure A.6 Downlink Horn Perimeter Beam, Total Pattern in XZ plane (*H*-plane)

The following figures show the *E* and *H*-plane normalized radiation patterns for the uplink pyramidal horns aboard the UAV.

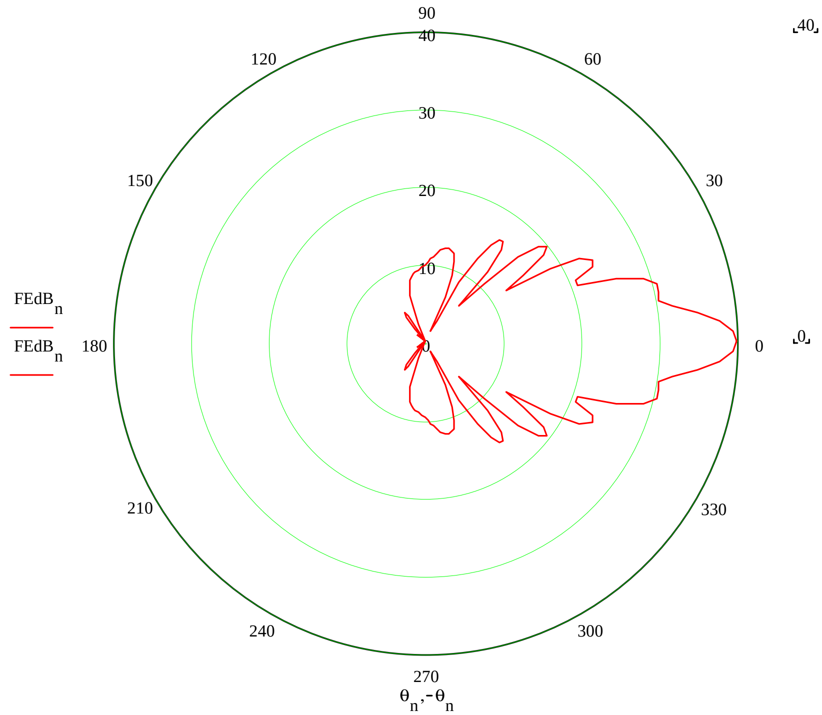

Figure A.7 Uplink Horn, Total Pattern in YZ plane (*E*-plane)

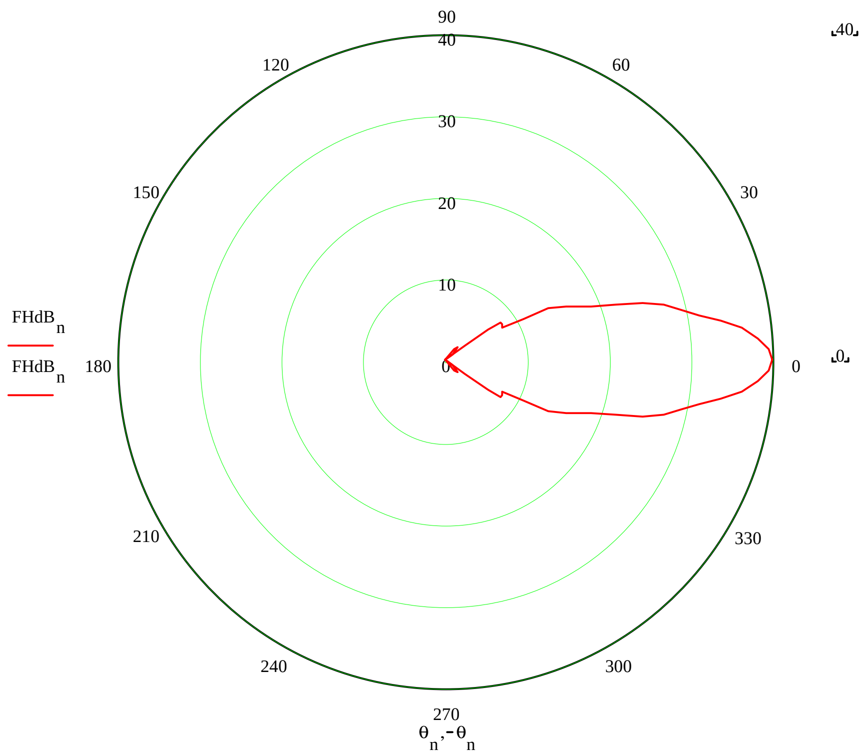

Figure A.8 Uplink Horn, Total Pattern in XZ plane (*H*-plane)

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