Low-cost Wireless Internet System for Rural India using Geosynchronous Satellite in an Inclined Orbit

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ABSTRACT

Providing affordable Internet access to rural populations in large developing countries to aid economic and social progress, using various non-conventional techniques has been a topic of active research recently. The main obstacle in providing fiber-optic based terrestrial Internet links to remote villages is the cost involved in laying the cable network and disproportionately low rate of return on investment due to low density of paid users. The conventional alternative to this is providing Internet access using geostationary satellite links, which can prove commercially infeasible in predominantly cost-driven rural markets in developing economies like India or China due to high access cost per user.

A low-cost derivative of the conventional satellite-based Internet access system can be developed by utilizing an aging geostationary satellite nearing the end of its active life, allowing it to enter an inclined geosynchronous orbit by limiting station keeping to only east-west maneuvers to save fuel. Eliminating the need for individual satellite receiver modules by using one centrally located earth station per village and providing last mile connectivity using Wi-Fi can further reduce the access cost per user. A Ku band system design for rural India based on this concept, using an Intelsat 906 satellite is proposed in this thesis. The path of the satellite and the tracking requirements at village stations are determined. Components required for various blocks of the system are defined. Modulation schemes, FEC, data rates, number of customers to be served, link availability and outage statistics are presented. Quantitative analysis using link budgets and ITU rain models are provided. An optimized system design and a commercial deployment model are suggested which show the system is economically feasible.

Dedicated to my parents,
Nilam and Rajan Desai

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Karan Desai

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Chapter 1

Introduction

The role of Internet and wireless communication in bringing about social and economic progress in the 21st century cannot be understated. Especially in developing countries, Internet can act as a catalyst for rapid economic development by providing a means of communication and allowing access to educational, medical and electronic commerce facilities. Keeping this in mind, several non-conventional approaches are being developed to provide affordable Internet access to those remote areas that are not connected by traditional communication means. This project proposes one such approach to provide low cost Internet access to rural areas using a combination of satellite link and Wi-Fi for last mile connectivity, focusing on cost reduction by the use of a communication satellite nearing its end of scheduled life, orbiting in an inclined geosynchronous orbit due to limited station-keeping maneuvers owing to limited fuel supply. The proposed system can be implemented in any country of the world, however, rural India has been chosen as the area of focus in this thesis and the reasons for this choice are explained in the subsequent sections.

1.1 Background

India is a democratic country located in south Asia. The geographical area of India is 3,287,263 sq. km making it the seventh largest country in the world by area. [1] The population of India as per 2010 Census is 1.18 billion. This makes India the second largest country in the world by population. The economy of India is traditionally agriculture based and a vast majority of the country's population resides in over 600,000 villages spread almost uniformly across the country. As a result, historically a considerable section of India's population has remained deprived of modern communication and entertainment facilities, usually made available only to profit making urban centers. However, in the last few years, cellular telephones and Internet usage has penetrated rural areas on a wide scale all over the world thanks to numerous wireless communication systems. Rapidly developing Asian economies such as India and China have been at the forefront in this change.

In the last five years, there has been a tremendous improvement in cell phone penetration in rural India and the nationwide teledensity has reached more than 55% with a total of 601 million cell phone users registered with the various GSM and CDMA providers in the country. [2] This has been made possible due to several efforts taken by the Indian federal government to improve rural connectivity. For example, the government has provided subsidy support for setting up mobile towers in the rural areas from the Universal Service Obligation Fund (USOF). However, the same is not the case with Internet penetration. The state-owned Bharat Sanchar Nigam Limited (BSNL) is the only widely recognized rural broadband Internet service provider in India. Long before the private Internet operators made foray into the broadband and Internet sector, BSNL had been offering Internet connectivity to major parts of rural India. Unlike private operators who have focused on densely populated urban circles, BSNL enjoys backing by the federal administration, which reflects in its wider reach into the farthest of villages. However, considering the geographical expanse of India, it is not possible for BSNL to single handedly provide Internet access to remote areas all over the country.

1.2 History of Internet Coverage in India

The first dial-up access to the Internet was given to the general public in 1989 by The World, an Internet service provider based in Massachusetts, USA. By 1995, there were 16 million Internet users in the world. However, the spread of Internet was limited to USA and a few European countries. The era of wireless personal communication started in India only 15 years ago, in August 1995, when the state-owned Videsh Sanchar Nigam Limited (VSNL) launched the first dial-up Internet service. Around the same time, the first commercial mobile phone service was introduced in the country. For the first three years, Internet service was provided solely by the state and the growth was slow. In 1998, a new telecom policy passed by the federal government allowed private Internet Service Providers (ISPs) to enter the Indian market. At that time, high speed Internet access was made available by various providers at speeds from 64 kilobits per second (kbps) onwards and an always-on Internet connection at 128 kbps was considered as Broadband. However, there was no uniform standard for broadband connectivity throughout the country.

Recognising the potential of broadband Internet service in growth of nation's GDP and enhancement in quality of life through societal applications including tele-education, telemedicine, e-governance, entertainment as well as employment generation by way of high-speed access to information and web-based communication, Government of India finalised a policy to accelerate the growth of broadband Internet services in 2004. According to Government of India's Broadband Policy, 2004, [3] broadband Internet connectivity is defined as follows- "An 'always-on' data connection that is able to support interactive services including Internet access and has the capability of the minimum download speed of 256 kbps to an individual subscriber from the Point Of Presence (POP) of the service provider intending to provide Broadband service where multiple such individual Broadband connections are aggregated and the subscriber is able to access these interactive services including the Internet through this POP." The Broadband Policy of 2004 estimated that by the end of 2010, there would be 20 million broadband Internet users in India. However, the actual number of broadband users at the end of June 2010 is only 9 million, much less than predicted in 2004. [4] The main reason for this is lack of broadband infrastructure in the rural areas.

1.3 Growth of Internet in India

The huge cost of creating and maintaining infrastructure in the low-income, sparsely populated rural areas discouraged the private Internet service providers from extending their broadband services to small villages and other remote areas. The Government of India has put in a lot of effort in trying to address the issue of wireless connectivity in rural areas. For example, it has provided subsidy support for mobile towers in the rural areas from the Universal Service Obligation Fund (USOF). As a result of this, cellular phone coverage is now available in several thousand villages throughout India. As of July 2010, there are 652 million cell phone subscribers in India [4] served by 13 mobile network operators, using GSM, CDMA, EDGE and EVDO technologies. The nationwide teledensity is 58.17%, which is expected to reach 75% by 2013. However, the penetration of broadband Internet has not been as extensive and as of July 2010, there are only 9.77 million broadband Internet subscribers in India, which is only 0.88% of the total population of India as per 2010 Census. The disparity in the growth rate of cellular phone subscribers and broadband Internet subscribers in India over the last three years can be seen in Fig. 1.1-

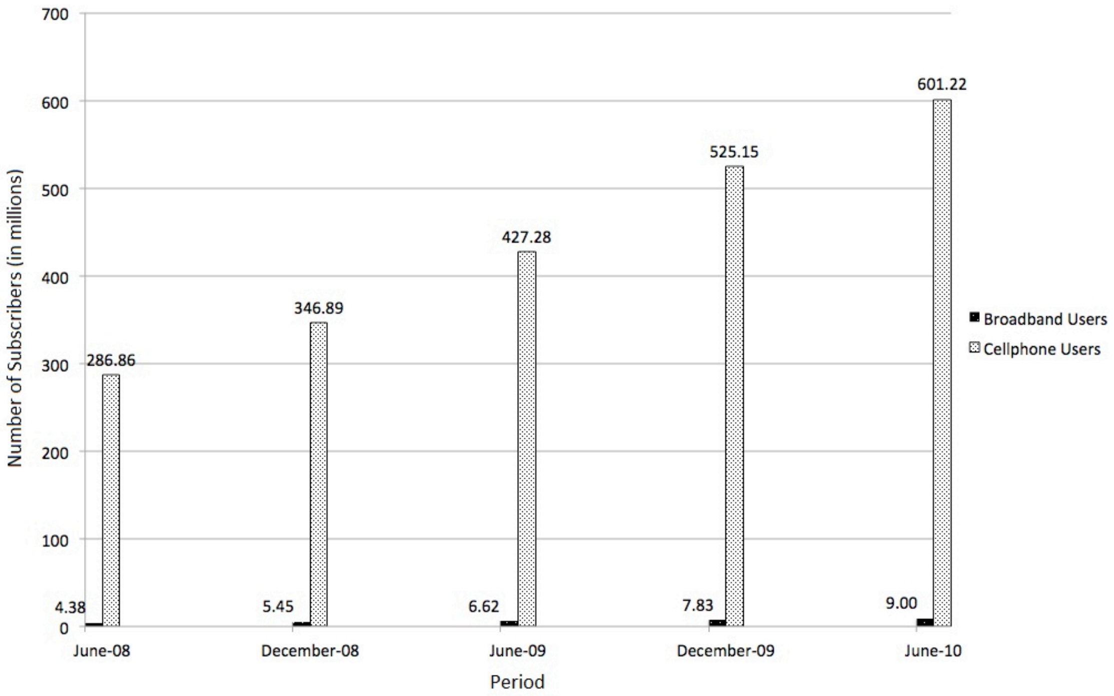


Fig. 1.1: Growth of Cellphone and Broadband Internet Users in India. Data sourced from [2], [3], [4]

The reason for rapid increase in the number of cell phone users has been the intense competition among the private telecom companies resulting in continuously lowering call rates, further aided by subsidized cell phone services provided by state-owned BSNL in the rural areas. As of July 2010, India has one of the lowest call rates in the world with the lowest tariff for outgoing phone calls being 0.4 cents per minute and the average call rates centered around 1 cent per minute, calculated as per prevailing exchange rates between Indian Rupee and US Dollar in July 2010. However, this has not been the case with broadband Internet service. As of July 2010, the lowest broadband Internet plan being offered in rural areas costs US $2.05 per month which provides up to 512 kbps download speed and restricts data download per month to 400 MB. [5] The lowest priced plan allowing unlimited data usage costs $10.25 per month, which is around six times the average monthly cell phone bill for rural customers. This shows there is a tremendous potential and an urgent need in the India for a low-cost Internet service capable of catering to the untapped rural market. Such a service would be beneficial from a social as well as economic point of view.

1.4 Extent of Internet Coverage in Rural India

The Indian economy is predominantly agriculture dependent. Approximately 750 million residents comprising 71 percent of India’s total population live in rural areas and practice agriculture as their profession. The 300 million Indians living in urban and suburban areas have benefited from the telecom and broadband policy of 2004 that opened up the market for private Internet service providers. The state-owned Mahanagar Telephone Nigam Limited (MTNL) provides cable Ethernet with speeds up to 8 Mbps and EVDO based wireless broadband Internet services in New Delhi and Mumbai. Bharat Sanchar Nigam Limited (BSNL) provides similar services in several other major cities. However, most of the smaller villages, comprising typically of 250 to 300 families, do not have access to even dial-up Internet services.

The Government of India is focusing on ways to make Internet accessible to a majority of the population, which lives in rural areas away from major cities. However, the major challenge lies in laying optical fiber or coaxial cable lines to provide broadband Internet access to small villages located in geographically difficult terrains. A possible solution to this problem lies in eliminating the need for cables by providing a wireless data link to the villages via satellite. However, the existing satellite Internet services, making use of geostationary satellites to provide Direct to Home (DTH) wireless Internet access are expensive and not suitable for implementation in rural India where low cost is the key to acceptance among the residents. The case of exponential growth in the number of cell phone users in rural India over the last three years has made it evident that a majority of the rural population in the country is open and enthusiastic to subscribe to means of modern communication provided it is made available to them at a rate that is affordable to small farmers and daily wage employees. This forms the basic premise and inspiration for this proposal to develop and implement a low cost wireless Internet system for rural India.

1.5 Growth and Extent of Wireless Internet

With the growing number of cell phone users in India, the use of Internet over mobile devices is also increasing. As of August 2010, the predominant technology in use to provide Internet access on mobile devices in India has been GPRS and EDGE. Typical data rates achievable over 2G cellular networks are in the range of 56 kbps to 112 kbps, which is lower than the threshold decided for broadband Internet and insufficient for multimedia applications such as video calls and streaming. The state owned BSNL has started providing EVDO based wireless Internet services in some of the major cities across India, [3] however, this remains limited to urban centers and the rural customers have no access to this technology. A map showing the spread of EVDO based wireless Internet service in India is shown in Fig 1.2.

Fig. 1.2: EVDO Wireless Internet Coverage in India by BSNL. Data sourced from [6]

It is evident from Fig. 1.2 that broadband wireless Internet services are concentrated in major urban centers. However, a majority of India's population lives scattered in villages all over the country, and in order to provide them access to educational, e-commerce and entertainment resources, it is essential to set up a wireless Internet system that is accessible from all villages and the most practical way of covering such a large geographical expanse is by making use of satellites to provide Internet services. The system proposed here is built upon this requirement.

1.6 Summary

Chapter 1 of this thesis presents an overview of the wireless connectivity in India, including the history and growth of Internet and cell phone services, government policies, extent of wireless Internet using various technologies and the market potential for a low-cost Internet system in rural India. Chapter 2 provides insight into the existing satellite Internet systems in use in developed countries and looks at reasons why these approaches would not be successful in developing economies. It also provides an overview of the socio-economic conditions and typical geographical layout of villages in developing economies. These chapters serve to justify the inspiration and motivation for undertaking this research project.

Chapter 3 provides an explanation of satellite orbit mechanics including Kepler's laws, the procedure to determine the azimuth and elevation angles of a satellite in orbit as well as the effect of various orbital perturbations on the motion of the satellite. This information is then used to determine the alignment of antennas on the earth stations. A brief description of graveyard orbits for parking aged satellites, and the procedure to launch and maintain a communication satellite is also provided. The two major cost reduction techniques being proposed - eliminating initial high cost of launching a communication satellite by using an existing geostationary satellite nearing the end of its active life, and eliminating the need for individual satellite receivers for each customer by using a single receiving hub providing last mile connectivity using Wi-Fi are explained in Chapter 4. This chapter also provides information about the satellite - Intelsat 906 –

chosen as an example, factors affecting the tracking and visibility of the satellite from earth stations and the effects of antenna beamwidth and gain on system performance.

The next chapter describes the building blocks of the system - the central hub, the satellite transponders and the village stations. A study of the various modulation and forward error correction that can be implemented in the proposed system, and its effect on data rates is included. Chapter 6 provides a quantitative analysis of the system performance by means of link budgets for inbound and outbound satellite links. A brief description of the weather pattern in India is given, followed by a quantitative analysis of the effect of rainfall on the satellite links and system availability. The chapter concludes with an optimized system design using adaptive modulation and FEC, capable of serving a larger population than envisaged in the original design. Finally, the economic feasibility of the project in terms of availability and population served, and a possible pricing model for commercial deployment is provided in Chapter 7.

Chapter 2

Motivation and Justification for the Project

2.1 Existing Satellite Internet Systems

The use of satellites to provide Internet access is not new. In 1973, two computers at a European research facility were connected to an American network via a satellite link. In 1996, the world's first consumer satellite Internet service was started in USA by DirecPC, which later came to be known as HughesNet. [7] Satellite Internet was originally marketed to Internet users in remote areas or users who did not have access to local points-of-presence (POP). This tradition continues even today and satellite Internet offers near-broadband speeds to customers who would otherwise have no data connectivity.

While satellite Internet service does offer access speeds approaching those of other broadband services, the actual throughput rates experienced by users are much lower due to high latency involved because of the large distance the data has to travel from the hub station to the satellite and back to the end users. Factoring in delays from network sources gives a typical one-way connection latency of 500–700 ms from the user to the ISP, or about 1,000–1,400 milliseconds latency for the total Round Trip Time (RTT) back to the user. This is much more than most dial-up users experience at typically 150–200 ms total latency. Most satellite Internet services provide unequal uplink and downlink rates, so many times the upload speeds are even slower, with upload throughput resembling that of dial-up connections. One way to reduce latency is to use Low Earth Orbit (LEO) satellites instead of geostationary ones. The current LEO constellations of Globalstar and civilian users of Iridium satellites have round trip delay around 340 ms because all signals are routed via gateways at each end of the link, but their throughput is 64 kbps, much less than broadband specifications. The Globalstar constellation orbits 1,420 km above the earth and Iridium orbits at 670 km altitude.

Satellite Internet works satisfactorily in clear weather. However users in locations with heavy rain may experience service interruptions as precipitation, snow accumulation, and heavy clouds can negatively affect the ability of the service to communicate with the orbiting satellite.

2.2 Problems Due to Prevailing Socio-Economic Conditions

Since all existing satellite Internet services use either dedicated geostationary satellites or leased bandwidth from other commercial satellites, the service is more expensive than conventional DSL and cable broadband services. As of November 2010, the two major Satellite Internet providers in USA- Hughes Net and Wild Blue have their lowest priced plans starting at US $50 per customer per month, with additional cost of equipment and installation of the system ranging from $400 upwards per customer. [8] An Internet system with these high costs would not work in a developing economy like India, considering it translates to around 2,000 Indian Rupees (INR) at prevailing exchange rates, which is close to the amount an average Indian farmer earns per month. However, the number of customers opting for the service would shoot up several times if the monthly cost to the end user can be brought down by a factor of ten, as has been seen in the case of cell phone usage in the country's rural areas.

In 1995 when the first cell phone service was launched in India, a handset cost around INR 29,000 and the outgoing call rate was INR 13 per minute. During the period these rates existed, the number of cell phone users grew slowly to only 3.6 million in five years. After the entry of private service providers and subsequent decrease in call rates, this number increased to 286 million by 2008. However, after 2008, intense competition between the service providers brought call rates down to less than INR 1 per minute, which has been the standard call rate for landline telephones in India. Once this barrier was broken, and the rural customers realized that it was cheaper to use a cell phone than a landline phone, there was a nationwide demand for cell phone connections, and between June 2008 and June 2010, India added 325 million new cell phone subscribers amounting to an average 450,000 new users added every day. This rapid acceptance of cell phones by the rural population brought about simply by lowering the monthly cost per customer proves that a low cost wireless Internet system has the potential of becoming immensely popular in rural India while being economically profitable for the service provider.

2.3 Peculiar Layout of Villages in India

According to Government of India 2001 census, [9] there are 593,731 villages in India and 742,490,639 people, comprising around 75% of the total population of India live in these villages. The size of these villages varies considerably- 236,004 villages have a total population less than 500 while 3,976 villages have a population over 10,000. However, there is a remarkable similarity in the geographical layout of villages across India. Most of the small villages across the country consist of a tight design with numerous small houses built close to one another, centered around a village square known as *chowk* or a religious structure such as a temple, mosque or a church. Several villages are located close to natural source of water such as a pond, lake or a river. Surrounding the closely spaced houses are farms and fields owned by villagers, spiraling outwards from the village's residential area. This uniformity in design is observed across all the states in India. Analysis of satellite images of Indian villages reveals that residential structures in small villages tend to be concentrated in a radius of 100 to 200 meters measured from the central square of the village. A few examples of this peculiar design are illustrated in Figure 2.1. The figure shows satellite images of a sample village from each region of India. Starting from top left and going clockwise, the first image is from Anand district in Gujarat state in western India, the second image is from Faridabad district in Uttar Pradesh state in north India, the third image is from Bhadrak district in Orissa state in eastern India while the fourth image is from Mysore district in Karnataka state in south India.

As seen in Figure 2.1, the average radius of a small village in India is between 100 and 200 meters measured from a central location in the village. This close spacing has an advantage from the point of view of providing communication services to the villages. For wireless communication services such as cellular phones, in most cases it is enough to construct only one base station and transmission tower per village. This has been one of the inspirations behind the proposal of a hub and spoke based model for Internet access discussed in this project. Since the area covered by a village in India is relatively small compared to the area covered by a village of similar population in North America or Europe, it becomes feasible to consider setting up a low-cost Internet access system using only one central hub per village connected to the ISP via satellite link and providing last mile connectivity using Wi-Fi. According to specifications laid down in IEEE 802.11n, the maximum outdoor range of Wi-Fi is approximately 250 meters. Considering this, it should be possible to cover an entire village that has customer premises located within a radius of around 150 meters from the center using a single transmitting station.

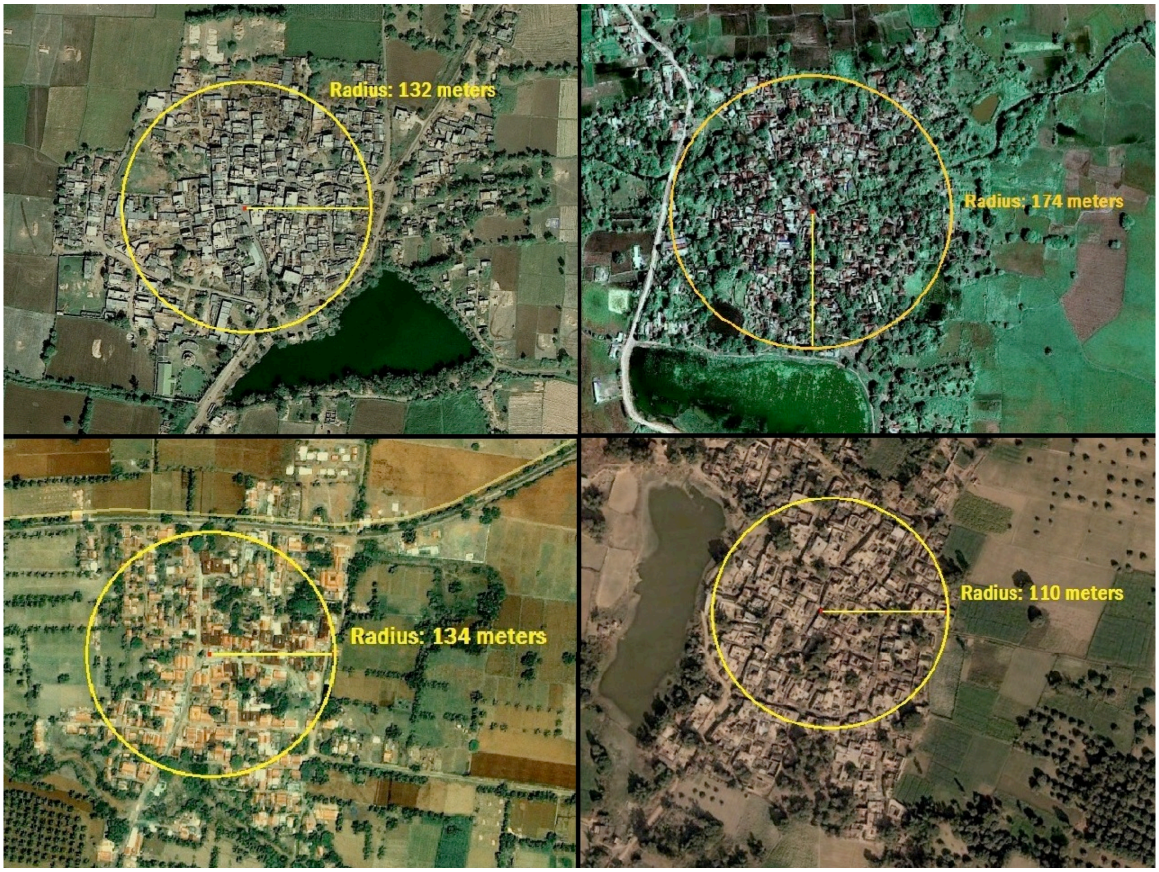


Fig 2.1: Satellite images showing similarity in village sizes in different regions of India. Sample villages, seen clockwise from top left, in Gujarat state in the west, in Uttar Pradesh state in the north, in Orissa state in the east, and in Karnataka state in the south. Image source and radius calculation using Google Earth software.

Chapter 3

Satellites - Orbits, Launch and Maintenance

3.1. Satellite Orbits

The motion of a satellite around its host body is governed by Kepler's Laws. To completely describe an orbit mathematically, six elements must be calculated. These elements are known as Keplerian elements, named after Johannes Kepler. These elements are semi-major axis, eccentricity, inclination, argument of periapsis, time of periapsis passage and celestial longitude. The orbital period, although not a Keplerian element, is important from satellite operational point of view.

Various orbits have been defined for spacecraft and satellites around the Earth and they can be classified on the basis of their altitude or inclination. On the basis of altitude, orbits about the Earth are classified as follows [10] -

Low Earth Orbit (LEO): These are geocentric orbits with altitude ranging from 0 to 2000 km from the surface of the Earth.

Medium Earth Orbits (MEO): These geocentric orbits range in altitude from 2,000 km to just below geosynchronous orbit at 35,786 km from the Earth's surface.

High Earth Orbit: These are geocentric orbits higher than geosynchronous orbit at 35,786 km.

Geostationary Earth orbit (GEO): This is a specific geocentric circular orbit at an altitude of 35,786 km from the surface of the earth and in the earth's equatorial plane.

The most important type of orbit from commercial point of view is the geosynchronous earth orbit. A geosynchronous orbit is an orbit around a planet with an orbital period that matches the planet's sidereal rotation period. A geosynchronous orbit around the Earth has an orbital period of 23 hours 56 minutes 4.091 seconds. While any orbit with this orbital period can be called a geosynchronous orbit, the term *geostationary* is often used to refer to the special case of a circular geosynchronous orbit at zero inclination, directly above the equator and is referred to as geostationary orbit. A satellite placed in geostationary orbit appears to be stationary above the Earth at a constant longitude, when viewed by an observer from the surface of the Earth.

The inclination is one of the six orbital parameters describing the shape and orientation of a celestial orbit. It is the angular distance of the orbital plane from the plane of reference, normally stated in degrees. For calculating inclination of satellites orbiting the Earth, the plane of Equator is usually taken as the plane of reference. On the basis of their inclination from the equatorial plane, orbits are classified as follows-

Polar orbit: These are the orbits that pass over both the poles of the parent planet. A polar orbit has inclination equal to, or very close to 90 degrees.

Polar sun synchronous orbit: This is a nearly polar orbit that passes the equator at the same solar time on every pass. It is useful for terrain imaging because the shadows on the ground will be the same on every pass of the satellite.

Equatorial orbit: This is an orbit whose inclination with respect to the Earth's equator is zero degrees. It is also called a non-inclined orbit.

Geosynchronous Transfer Orbit (GTO): It is a temporary elliptical orbit that a spacecraft scheduled to attain geostationary orbit enters before being inserted into the circular GEO orbit. The capability of spacecraft launch vehicles is usually compared by the mass they are capable of lifting up to GTO.

3.2. Geostationary Satellites

Kepler's third law of planetary motion states that the square of the orbital period of a planet or satellite is directly proportional to the cube of the semi-major axis of its orbit. In accordance with this law, there must exist exactly one value of semi-major axis of a circular satellite such that the period of revolution of the satellite is exactly equal to the time of one rotation of the Earth - one sidereal day of 23 hours 54 minutes 4.091 seconds. The value of radius of the orbit, *r* that satisfies this condition is given by

$$r^3 = \frac{GM}{\omega^2} \rightarrow r = \sqrt[3]{\frac{GM}{\omega^2}} \quad \ldots(3.1)$$

The product *GM* is known as the geocentric gravitational constant and its value has been accurately calculated [5] to be μ = 398,600.4418 ± 0.0008 km^3 s^{-2} also called Kepler's constant. In terms of Kepler's constant, we have

$$r = \sqrt[3]{\frac{\mu}{\omega^2}} \quad \ldots(3.2)$$

The angular velocity ω is found by dividing the angle travelled in one revolution by the orbital period, which in this case is one sidereal day, or 86,164.09054 seconds. This gives $\omega = 7.2921 \times 10^{-5}$ radians/second. Substituting this value in Eq. 3.2, the resulting orbital radius is 42,164 kilometers. Subtracting the Earth's mean equatorial radius - 6,378 kilometers from this value gives the altitude of the geostationary orbit as 35,786 kilometers from the Earth's surface for the geostationary orbit. This is a theoretical value. In practice, factors such as lunar gravity, solar gravity and the flattening of the Earth at its poles results in deviation of the geostationary satellite from its orbit causing the satellite to drift up to a maximum inclination of 15 degrees over a period of 26.5 years. In order to correct this orbital perturbation, repeated station keeping maneuvers are required.

3.3 Satellite Orbit Mechanics

Kepler's first law of planetary motion states that the orbit of any satellite is an ellipse. In order to mathematically describe the properties of this orbit and locate the satellite in orbit, we first need to define a rectangular co-ordinate system (x_o, y_o, z_o) in which the x and y co-ordinates lie in the orbital plane and z_o is normal to it. Some of the mathematical calculations involved become easier to solve if expressed in the polar co-ordinate system (r_o, ϕ_o) where r_o is the radius vector and ϕ_o is the angle measured counter clockwise from the positive x_o axis. [11]

The equation of orbit [10] is given by

$$r_0 = \frac{\left(\frac{h^2}{\mu}\right)}{1 + \left(\frac{h^2}{\mu}\right) C \cos(\phi_0 - \theta_0)} \qquad \ldots(3.3)$$

For $e < 1$, this is the equation of an ellipse whose semilatus rectum p is given by

$$p = \frac{h^2}{\mu}$$

and whose eccentricity e is h^2C/μ. Under the limiting condition $e = 0$, this orbit is a circle with the earth at its center. This is the orbit of importance as far as this project is concerned. The quantity θ_0 describes the orientation of the ellipse with respect to the orbital plane. If we choose x_0 and y_o such that θ_0 is zero, the equation of orbit becomes

$$r_0 = \frac{p}{1 + e\cos\phi_0} \qquad \ldots(3.4)$$

The lengths of the semi-major axis a and semi-minor axis b are given by [12]

$$a = \frac{p}{1 - e^2} \qquad \ldots(3.5)$$

$$b = a(1 - e^2)^{1/2} \qquad \ldots(3.6)$$

Using this, in the plane of orbit, the equation of orbit can be written as

$$r_0 = \frac{a(1-e^2)}{1+e\cos\phi_0} \qquad \ldots(3.7)$$

The angle ϕ_0 is called the true anomaly. The parameters that define the satellite orbit are shown in Fig 3.1

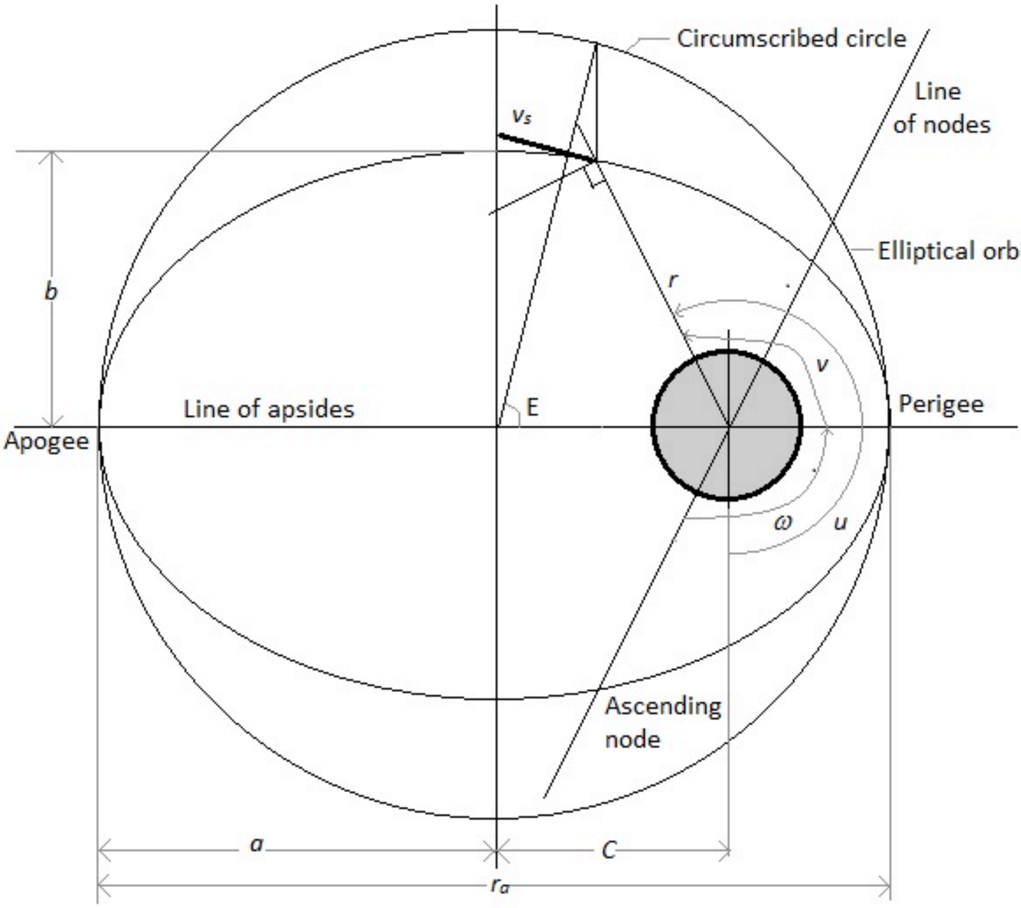


Fig 3.1: Parameters defining orbit of a satellite. Terms in the figure explained in the text. Drawn based on data from [11]

True Anomaly (ϕ_0) – an angle between 0° and 360°, measured positively in the direction of movement of the satellite, between the direction of perigee and the direction of the satellite.

Eccentric Anomaly (*E*) – the argument of the image in the mapping which transforms the elliptical trajectory into its principal circle. The procedure to find eccentric anomaly is as follows- locate the point where a vertical line drawn from the position of the satellite intersects the circumscribed circle. Draw a line from this point to the center of the ellipse. The angle made by this line with the x_o axis is the eccentric anomaly, *E.* In case of circular orbits where the center of the ellipse coincides with the center of the earth, the distance r_o of the satellite from the center of the earth can be written as-

$$r_o = a\,(1 - e\cos E) \qquad \ldots(3.8)$$

Mean Movement (η) – defined as the mean angular velocity of the satellite of period T in its orbit.

$$\eta = 2\pi/T \qquad \ldots(3.9)$$

Mean Anomaly (M) – the true anomaly of a satellite in a circular orbit of the same period T. The mean anomaly is expressed as a function of time as follows-

$$M = (2\pi/T)\,(t - t_p) = n\,(t - t_p) \qquad \ldots(3.10)$$

Here, t_p is the instant of passing through the perigee. The mean anomaly is related to the eccentric anomaly by Kepler's equation-

$$M = E - e\sin E \qquad \ldots(3.11)$$

These parameters allow locating the satellite at a point in the orbital plane. However, of special interest to us is the procedure to locate the position of satellite from a point on the rotating surface of the earth, since this is where the central hub station and all the village hubs will be located. In order to accomplish this task, we begin with a fixed rectangular co-ordinate system (x_i, y_i, z_i) called the *geocentric equatorial co-ordinate system*. [13]. The origin of this system is the center of the earth. The z_i axis coincides with the earth's axis of rotation and passes through the geographic North Pole. The x_i axis points towards a fixed location in space called the *first point of Aries*. As the earth revolves around the sun this co-ordinate system translates through space, but does not rotate. The (x_i, y_i) plane contains the earth's equator and is called the equatorial plane.

The position of the orbital plane in space is specified using two parameters - the inclination (i) and right ascension of the ascending node (Ω). These parameters are defined as shown in Figure 3.2 with respect to a co-ordinate system whose origin is the center of mass of the earth.

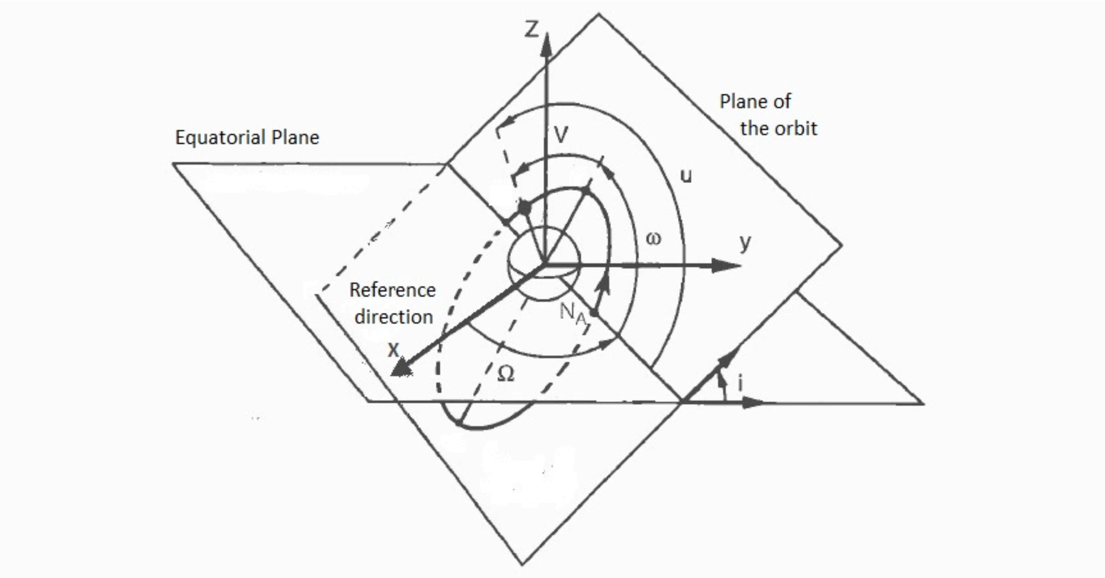


Fig 3.2: Positioning of satellite orbit in space. Drawn based on data from [11]

Inclination of plane of orbit (*i*) – the angle between the orbital plane of the satellite and the earth's equatorial plane, measured positive in the forward direction between 0^o and 180^o. For an inclination less than 90^o, the satellite rotates eastwards in the same direction as the earth, and for inclination greater than 90°, the satellite rotates westwards, opposite to the direction of rotation of earth.

Right Ascension of the Ascending Node (Ω) – the angle between the reference direction and ascending node of the orbit that is the intersection of the orbit with the plane of equator and is measured from 0° to 360°

Argument of Perigee (ω) – the angle between the ascending node and the direction of perigee, measured from 0° to 360° in the direction of motion of the satellite.

Knowledge of six parameters - semi-major axis (a), eccentricity (e), inclination (i), right ascension of the ascending node (Ω), time of perigee (t_p) and argument of perigee (ω) completely defines the trajectory of a satellite in space. The nodal angular elongation (u) can also be used to define the position of the satellite in its orbit. This is the angle between the ascending node and the direction of satellite, measured positively from 0° to 360° in the direction of motion of the satellite. This parameter is useful in the case of a circular orbit where the perigee is unknown.

3.4 Look Angle Determination

The co-ordinates at which the earth station antenna must be pointed to communicate with the satellite are called look angles. For the proposed system, the look angles must be calculated for the central hub as well as for each of the village stations. In the case of village stations, the antenna needs to be pointed at the correct look angles at the time of installation since the hub stations will be located in remote areas and will not have any station-keeping staff.

Look angles are specified in terms of azimuth (Az) and elevation (El). Azimuth is measured eastward from the geographic north at the earth station to the projection of the satellite path on a horizontal plane at the earth station. Elevation is the angle measured vertically upward from this horizontal plane to the path to satellite. For geostationary satellites, look angles can be conveniently calculated using geographic co-ordinates of the subsatellite point. This is the point where a line drawn from the center of the earth to the satellite passes through the earth's surface. For an ideal geostationary satellite, the subsatellite point is a fixed longitude and requires no calculation. However, in the case of slightly inclined geostationary satellite being used for this project, the subsatellite point will vary, lying in a small area around the point where it should be located for the given satellite when it was being kept in perfect geostationary orbit.

Figure 3.2 shows the geometry for elevation angle calculation. In the figure, $\mathbf{r}_s$ is the vector from center of the earth to the satellite, $\mathbf{r}_e$ is the vector from the center of the earth to the earth station and **d** is the vector from the earth station to the satellite. Angle γ is the central angle between earth station and satellite and ψ is the angle measured from $\mathbf{r}_e$ to **d**. Defined so that it is non-negative, γ is related to the earth station north latitude L_e and west longitude l_e and subsatellite point north latitude L_s and west longitude l_e by

$$\cos(\gamma) = \cos(L_e)\cos(L_s)\cos(l_s - l_e) + \sin(L_e)\sin(L_s) \qquad \ldots(3.12)$$

Using trigonometry [13] yields

$$\cos(El) = \frac{\sin(\gamma)}{\left[1 + \left(\frac{r_e}{r_s}\right)^2 - 2\left(\frac{r_e}{r_s}\right)\cos(\gamma)\right]^{1/2}} \qquad \ldots(3.13)$$

Using equations (3.12) and (3.13), it is possible to calculate the elevation angle *El* provided the subsatellite and earth station co-ordinates, orbital radius r_s and the earth's radius r_e are known. A generally accepted value for the earth's radius r_e is 6370 km.

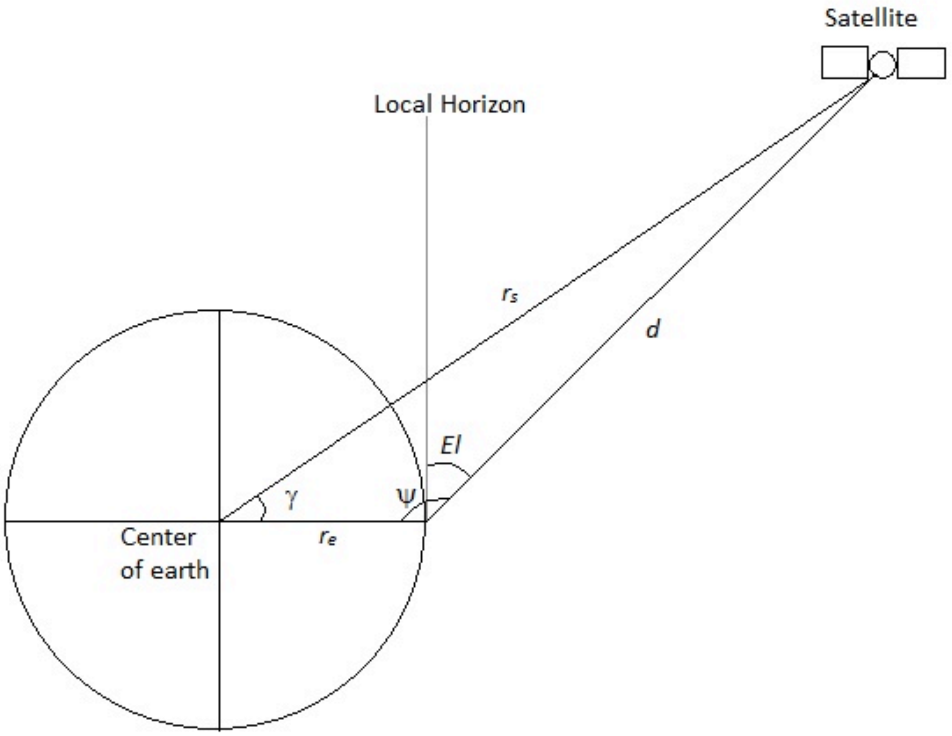


Fig 3.2: Geometry of elevation angle calculation. Based on data from [12]

For geostationary satellites, subsatellite points are on the Equator at longitude l_s while latitude L_s is 0. The geosynchronous radius is fixed with value r_s = 42,242 km. Considering this, for geostationary satellites, equation (3.16) reduces to

$$\cos(\gamma) = \cos(L_e)\cos(l_s - l_e) \qquad \ldots(3.14)$$

The distance *d* from the earth station to the geostationary satellite in km is given by

$$d = 42242\,[1.02274 - 0.301596\cos(\gamma)]^{1/2} \qquad \ldots(3.15)$$

The elevation angle El is given by

$$\cos(El) = \frac{\sin(\gamma)}{[1.02274 - 0.301596\cos(\gamma)]^{1/2}} \qquad \ldots(3.16)$$

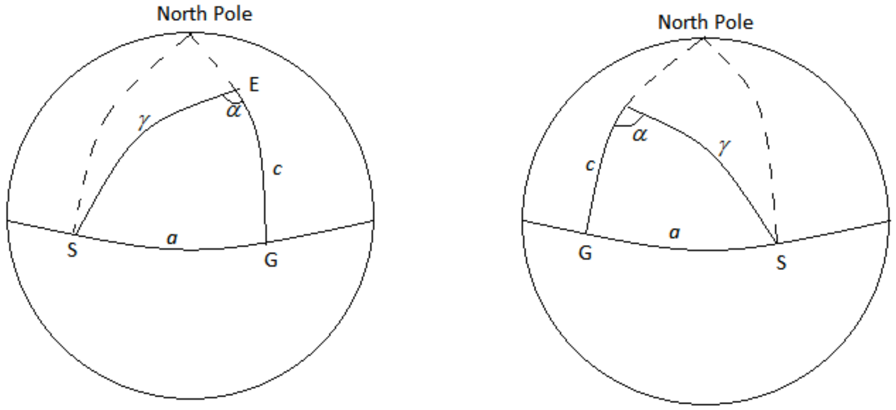
Since the satellite, subsatellite point, earth station and center of the earth all lie in the same plane, the azimuth angle Az from an earth station to the satellite is same as the azimuth from center of the earth to the subsatellite point. This fact is used in the derivation of equations for azimuth calculation. [13] The calculation of azimuth for geostationary satellites is relatively simplified compared to the general case and the derivation is based on the spherical triangle with the three vertices being the earth station (E), the subsatellite point (s) and the point where the longitude line of earth station crosses the Equator (G). The three sides of this triangle are arcs of length γ, a, and c as illustrated in Figure 3.3. The angle α at the vertex is given by

$$\alpha = 2\tan^{-1}\{\frac{\sin(s-\gamma)\sin(s-|L_e|)}{\sin(s)\sin(s-|l_e-l_s|)}\}^{1/2} \qquad \ldots(3.17)$$

The azimuth angle Az is related to α by the equations given in Table 3.1.

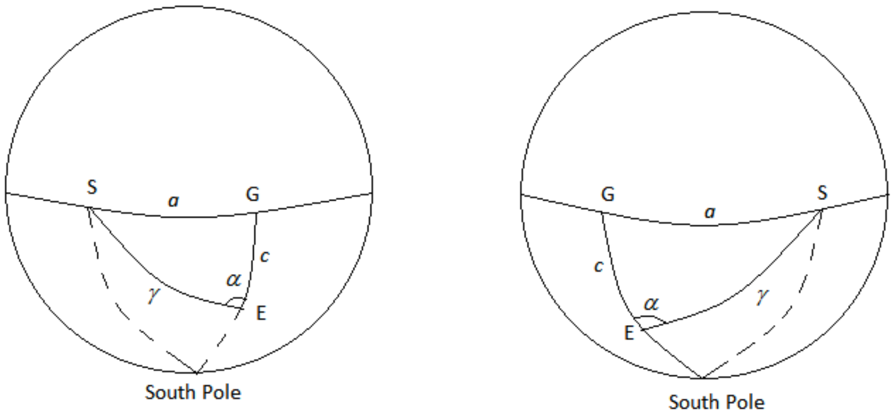
Situation	**Equation**
Satellite point southwest of earth station	$Az = 180^o + \alpha$
Satellite point southeast of earth station	$Az = 180^o - \alpha$
Satellite point northwest of earth station	$Az = 360^o - \alpha$
Satellite point northeast of earth station	$Az = \alpha$

Table 3.1: Equations for calculating Azimuth Az from Spherical Triangle Angle α [13]



(a) Sub-satellite point southwest of earth station
$Az = 180^\circ + \alpha$

(b) Sub-satellite point southeast of earth station
$Az = 180^\circ - \alpha$



(c) Sub-satellite point northwest of earth station
$Az = 360^\circ - \alpha$

(d) Sub-satellite point northeast of earth station
$Az = \alpha$

Fig 3.3: Spherical trigonometry of azimuth calculation. Drawn based on data from [14]

For the satellite to be visible from earth station, its elevation angle must be non-negative, which places a limit on the maximum angular separation between earth station and subsatellite point. For nominal geosynchronous orbit, the requirement for visibility is $\gamma < 81.3^\circ$. [14]

A satellite in an inclined orbit has varying L_s. If we plot the *Az-El* angles for the satellite as seen from the earth stations for several values of inclined orbit, it will give the figure of eight in the sky that the inclined orbit satellite should follow.

3.5 Orbital Perturbations

The equations mentioned in Section 3.3 are based on the assumption that the earth and the satellite are point masses, influenced only by their mutual gravitational attraction. Under these conditions, the satellite orbits the earth in a pure Keplerian elliptical orbit whose properties remain constant with time. However, in practice, the satellite is subjected to effects of asymmetry of the earth's gravitational field, the gravitational fields of the sun and the moon and solar radiation pressure. If left unchecked, these effects cause the subsatellite point of a geosynchronous satellite to move with time.

The earth is not a perfect sphere, being flattened at the poles. In addition, there are regions called *Mascons* where the average density of the earth appears to be higher. This causes a non-uniform gravitational field around the earth. Any external unbalanced force on the geostationary satellite causes it to accelerate and drift out of its orbit. Due to Mascons and equatorial bulges, there are four equilibrium points in the geostationary orbit - two stable equilibrium points at 75^o E and 252^o E, and two unstable equilibrium points at 162^o E and 348^o E. [14] If a geostationary satellite located at a stable point is perturbed, it tends to drift back to the stable point. A satellite perturbed from an unstable equilibrium point starts drifting towards the nearer stable point. On reaching the stable equilibrium point the subsatellite point oscillates in longitudinal position around this point until it stabilizes at that point after a very long time.

The plane of the earth's orbit around the sun, the sun's equatorial plane, the earth's equatorial plane and the moon's orbital plane around the earth are all inclined to each other at different angles. As a result, a satellite in orbit around the earth is subjected to out-of-plane forces that tend to change the inclination of satellite's orbit from its initial inclination. The net effect of acceleration forces induced by the moon and the sun on a geostationary satellite is to change the plane of its orbit at an initial rate of change of 0.85^o per year from the equatorial plane. [14]

Under normal circumstances, ground station controllers responsible for station keeping of the geostationary satellite command maneuvers to correct for longitudinal drifts as well as inclination drifts. The north-south maneuver to maintain the plane of the satellite requires much greater energy than east-west maneuver to maintain the longitude of an orbit, the difference in energy requirement being about 10:1. [10] If it is decided to stop the north-south maneuvers for a particular satellite when it is nearing the end of its active life and use the remaining fuel onboard the satellite solely for east-west maneuvers, the operational life of the satellite can be increased considerably, although the satellite will no longer be perfectly geostationary, instead the elevation and azimuth angles of the satellite will change continually over a sidereal day about its original location in the geostationary orbit, forming a figure-of-eight pattern when observed from an earth station. An analysis of the possibility of using this concept towards developing a low cost satellite Internet system forms the core of this project

3.6 Supersynchronous Graveyard Orbit

A graveyard orbit, also called a supersynchronous orbit, is an orbit significantly above the geosynchronous orbit where satellites are intentionally placed at the end of their operational life. It is a measure performed to lower the probability of collisions with operational satellites and to open up a location in the geostationary orbit for another satellite. A graveyard orbit is used when the change in velocity, Δv required to perform a de-orbit maneuver is too high. De-orbiting a geostationary satellite requires a Δv of about 1,500 m/s while the procedure to place it into a graveyard orbit requires about 11 m/s. [15]

For satellites in a geostationary orbit and geosynchronous orbits, the graveyard orbit is a few hundred kilometers above the operational orbit. According to the Inter-Agency Space Debris Coordination Committee (IADC) [15] the minimum perigee altitude for the graveyard orbit, ΔH above the geostationary orbit is:

$$\Delta H = 235km + (1000 C_R \frac{A}{m}) km \qquad \ldots(3.18)$$

where C_R is the solar radiation pressure coefficient (typically between 1.2 and 1.5) and A/m is the aspect area to mass ratio (m^2/kg) of the satellite. This formula includes 200 km for the GEO protected zone to permit orbit maneuvers in GEO without interference with the graveyard orbit and an additional 35 kilometers tolerance is allowed for the effects of solar and lunar gravitational perturbations. The remaining part of the equation considers the effects of the solar radiation pressure, which depends on the physical parameters of the satellite.

In order to obtain a license to provide telecommunications services in the United States, the Federal Communications Commission (FCC) requires all geostationary satellites launched after March 18, 2002, to commit to moving to a graveyard orbit at the end of their operational life. U.S. government regulations require a boost, ΔH, of ~300 km. [15]

3.7 Launch and Maintenance of Geostationary Satellite

The launch of a geostationary satellite used for satellite Internet is a complex, time consuming and expensive procedure. A typical geostationary satellite weighs around 3000 kilograms and requires specialized launch vehicles to place it into the correct orbit. The launch is carried out by a national space agency such as NASA or by commercial launch service providers. International Launch Services (ILS) based in Reston, VA is one such provider. The steps involved in preparing, launching and placing a geostationary satellite in orbit can be understood clearly using an example. Here, the Proton launch vehicle developed by Russia is used as a case study. [16]

The Proton is a geostationary satellite launch vehicle developed from an inter-continental ballistic missile (ICBM) by the erstwhile Soviet Union that has been used for 323 operational launches as of July 2009. The launch vehicle consists of four stages. The first three stages of the Proton inject the satellite-carrying vehicle into a sub-orbital trajectory. After the third stage separation, the first of five main engine burns is initiated that injects the vehicle into a standard low earth parking orbit. After coasting in the parking orbit for about 50 minutes, the second burn takes place near the first passage of the ascending node. This second burn serves as an initial phase of the process of raising the transfer orbit apogee to the geosynchronous apogee altitude. This burn transfers the vehicle into an intermediate transfer orbit with an apogee of 5000 to 7000 km. After coasting for one revolution in the intermediate orbit, the third and the fourth burns take place across the second ascending node. This fourth burn raises the apogee of the transfer orbit to the altitude of a Geosynchronous Orbit (GEO). The perigee altitude, as well as the transfer orbit inclination, can be modified somewhat in the course of the mission optimization that takes place during the mission integration phase. After approximately five hours in the transfer orbit, the fifth burn is initiated which raises perigee and lowers inclination into a Geosynchronous Transfer Orbit (GTO) with the desired target orbit parameters. When this burn is completed, a maneuver is performed to orient the satellite for separation, which takes place within 12 to 40 minutes of the end of the final burn. The total time of the standard mission profile from lift-off to satellite separation is approximately nine hours.

As seen from this example, launching a geostationary satellite is a complex procedure requiring high level of precision and hence the cost for conducting a single launch is also high. A publicly available figure of cost of launching a satellite into geostationary orbit using NASA or Russian facilities is $ 20,000 per kilogram of payload. For a satellite weighing 3,000 kilograms, this translates to a launch cost of US $ 60 million. In April 2010, the Indian Space Research Organization (ISRO) announced its plans of developing Geosynchronous Satellite Launch Vehicle (GSLV) using a semi-cryogenic engine that uses purified kerosene instead of liquid hydrogen fuel which would bring down the cost of launching communication satellites by half. [17] Even if this project proves to be successful, it would cost around US $ 30 million to place a heavy GEO satellite providing Internet services in orbit. In addition to these costs, maintenance and operations cost of a geostationary satellite is in the range of US $5 million per year. Moreover, each end user is required to purchase a receiver and antenna, which costs $300 at rates existing in USA in November 2010. Since this project is looking for a low cost solution aimed at making Internet services available in rural areas at an average cost of US $ 1 per customer per month, it is evident that launching and maintaining a dedicated satellite for this purpose is economically not feasible. Thus, it is necessary to look for ways to reduce the initial capital investment, which forms the basis of this project.

Chapter 4

Design of Low Cost System

4.1 Possible Ways of Cost Reduction

As seen in the previous chapter, a major cost component of setting up a satellite based Internet system is launching of a geostationary satellite and maintaining it in GEO orbit throughout the operational lifetime of the satellite. As a result, most existing commercial satellite Internet systems in use today in USA charge their customers around US $50 per month for broadband Internet access. This project envisions a low-cost system for use in rural India where the current lowest tariff for cable-based broadband is approximately US $10 per customer per month. Our target is to design a system that provides broadband Internet access in rural areas at costs in the range of US $1 per customer per month. To achieve this objective, cost reduction alternatives are required in two areas - the geostationary satellite and the receiver equipment installed at customer premises. Design and analysis of these alternatives forms the core of this project. The proposed methods of cost reduction are described in the following sections.

4.2 Use of Existing Geostationary Satellite

As of December 2010, there are more than 160 communication satellites owned by 23 countries or space agencies in the geostationary orbit. Some of these satellites were launched more than 15 years ago while some have been in orbit for less than a year. Most of the geostationary satellites have a design lifespan of 15 years. As a result, several satellites launched in the period between 1995-1996 have reached the end of their designed lifespan but are still in active operation. Each of these communication satellites is typically equipped with, on an average, 12 to 48 Ku-band and C-band transponders for bent-pipe operation. [10] All these satellites were launched with specific purposes such as television broadcast, satellite Internet, dedicated data communication links for military purposes, etc. However, the transponders can be used for purposes other than originally intended if the uplink and downlink data streams are digitally modulated and transmitted according to the design parameters of the specific transponders.

Several communication satellites have some or all of their transponders in working condition at the end of their design lifespan. FCC regulations require all communication satellites reaching the end of life to be shifted to a graveyard orbit approximately 300 km higher than the geostationary orbit. The satellite moved into the graveyard orbit then continues to orbit the Earth but serves no commercial purpose and is said to become a part of space debris. However, an agreement may reached with the satellite operator that when the satellite has only a limited quantity of fuel left onboard, for example 10% of the total stock carried at liftoff, the north-south station-keeping maneuvers can be discontinued, thereby using the remaining fuel only for east-west maneuvers. By doing this, the satellite can be kept at the correct longitude, but its orbit will steadily become more and more inclined to the equatorial plane at a rate of about 0.85 degrees per year. Since north-south station keeping typically requires ten times more fuel than east-west station keeping, this adjustment allows the satellite to remain in orbit for a much longer period and it can be used until the transponders fail. However this is a theoretical limit. In practice, this adjustment should allow the satellite to remain operational for five to ten years beyond its scheduled end-of-life. The satellite can now still be used to relay data between two or more earth stations, however, it is no longer in the geostationary orbit and hence when seen from the surface of the Earth, it no longer appears stationary at one point in the sky. The satellite is now in a slightly inclined geostationary orbit (SIGSO) and when seen from a point on the earth's surface, it traces a narrow figure of eight in the sky that crosses the GEO orbit at the center of the figure of eight.

Several satellites that have reached their scheduled end of life have been pushed out from the geostationary orbit into graveyard orbits as per FCC specifications. Some of these satellites have operational transponders onboard. It is also possible to revive one of these satellites to be reused for data relay services. However this is not a feasible alternative. A satellite at an orbit 300 km above the geostationary orbit has a period that is longer than a sidereal day. The orbital period can be calculated using Kepler's third law. Considering the mass of the Earth to be the generally accepted value 5.9737 x 10^{24} kg and assuming the Earth to be a perfect sphere with mean radius 6371 km, the orbital period of a satellite in graveyard orbit 300 km above the geostationary orbit is 87063.18 seconds corresponding to 24.182 Earth hours. As a result, when seen from an earth station, the satellite appears to be drifting to the west. Also, if the orbit is not inclined, it will pass behind another geostationary satellite every 2 degrees around the GEO orbit. As a result, the satellite cannot be used for communication services because of interference with other satellites.

4.3 Elimination of Receivers for Individual Customers

Commercially available conventional satellite Internet systems require each customer to purchase a dish antenna costing more than US $100. If the same business model is replicated in rural areas in developing economies, the initial investment exceeds the average monthly income of the residents, thereby diminishing their interest in subscribing to satellite Internet. However, if this initial investment for individual customers can be eliminated, a monthly access cost of around US $1 makes the system economically feasible for the rural population and paves the way for wide scale penetration of Internet into rural areas.

The proposed system involves elimination of satellite receivers for individual customers. The connection of end users to the ISP is via a village station. A central network operations hub located in an urban area connects to the Internet backbone. The central hub uplinks several channels of digitally modulated Internet data to the satellite which forwards the channels to the village stations. The village hub receives an Internet data stream as downlink from the satellite and acts as a Wi-Fi hotspot. The hub station thus creates a wireless local area network (WLAN) in accordance with IEEE 802.11n protocol for a small geographic area, covering the size of an average village. Other technologies such as ZigBee provide longer range but lower data rates. Also, customers are required to purchase ZigBee enabled devices. On the other hand, if Wi-Fi is used, the only investment required from the customers is purchasing a Wi-Fi enabled device that can connect to the village WLAN. Most commercially available laptop computers and several models of cellular phones and tablet computers come with in-built wireless network interface card (WNIC) allowing the device to connect to Wi-Fi hotspots.

If the satellite being used is not geostationary, a fixed antenna directed towards the satellite is not able to receive data from the satellite continuously. One way to receive a continuous stream of data from a satellite not in geosynchronous orbit is to steer the antenna in accordance with the flight path of the satellite. Elaborate tracking of satellite orbit to ensure the axis of beamwidth of the antenna always points exactly at the satellite requires a computer at the receiver station and substantial power to physically steer the antenna from time to time. This proves to be an impediment in developing a low cost Internet system. However, it is possible to program the antenna to track in one plane if the antenna uses a polar mount. A simple PIC processor and a stepper motor can be set up to follow the change in angle over a sidereal day. Given a single antenna in a village, this is a feasible option. All the old C-band television receive-only (TVRO) dishes from the 1980s had one plane tracking, with a jacking screw and a controller, used to select satellites in the GEO orbit. The dish had a polar mount so that motion on one axis caused the beam to track the GEO orbit over a substantial east-west arc. This should enable Internet access for a major part of the day.

4.4 Selection of Satellite

There are several communication satellites in geostationary orbit that were launched in the period between 1998 and 2001, which will reach their scheduled end-of-life between 2011 and 2015. For the implementation of the system proposed here, any satellite that has neared the end of its scheduled lifetime but is still in active service can be selected, so that some of its last remaining fuel stock can be used for limited station-keeping to maintain the satellite approximately around the longitude that allows the regional beams of the satellite to cover most of India’s mainland.

As an example of a typical aging GEO satellite, the satellite selected is Intelsat 906, launched on 6th September 2002, carrying a payload of 72 C-band transponders and 24 Ku-band transponders, currently providing direct-to-home video channels to Asia and the Indian subcontinent. Since the transponders onboard Intelsat 906 are bent pipe type, the satellite can be reused for a purpose different from its original use. This makes it possible to use Intelsat 906 to provide Internet services to rural India. Figure 4.1 shows the footprint of Intelsat 906 from its existing geostationary slot at 64^o East longitude. When pushed out to a slightly inclined geosynchronous orbit around the same longitude, the footprint will remain similar to what is seen in Figure 4.1. Some of the important parameters of Intelsat 906 are presented in Table 4.1 below.

Parameter	**Value**
Satellite position	64^o East over the Equator
Launch mass	4723 kg
Dry mass	1900 kg
Satellite type	Three axis body stabilized
Satellite model	Space Systems Loral (SS/L) 1300 Series
Beacons	3947.5, 3952.5R, 11198
Transponders	72 C-band, 22 Ku band

Table 4.1: Intelsat-906 Technical Data [20]

Intelsat 906 is a part of a group of seven satellites that were launched by Intelsat Inc. within a period of 20 months starting in 2001. The satellite has a rectangular body with a 30.5 m solar-array span. It has sun-tracking solar arrays and NiH_2 batteries. Intelsat 906 currently has two active Ku band beams - Spot beam 1 serving Pakistan and Middle East, and Spot beam 2 serving most of continental India. The existing footprint of this beam is illustrated in Figure 4.1. The reception details for spot beam 2, which is used for calculations for this project, are given in Table 4.2.

Parameters	**Values**
Elevation angle	17.7^o
True azimuth	90^o
Magnetic azimuth	96^o

Table 4.2: Intelsat-906 Spot Beam 2 Reception Parameters [20]

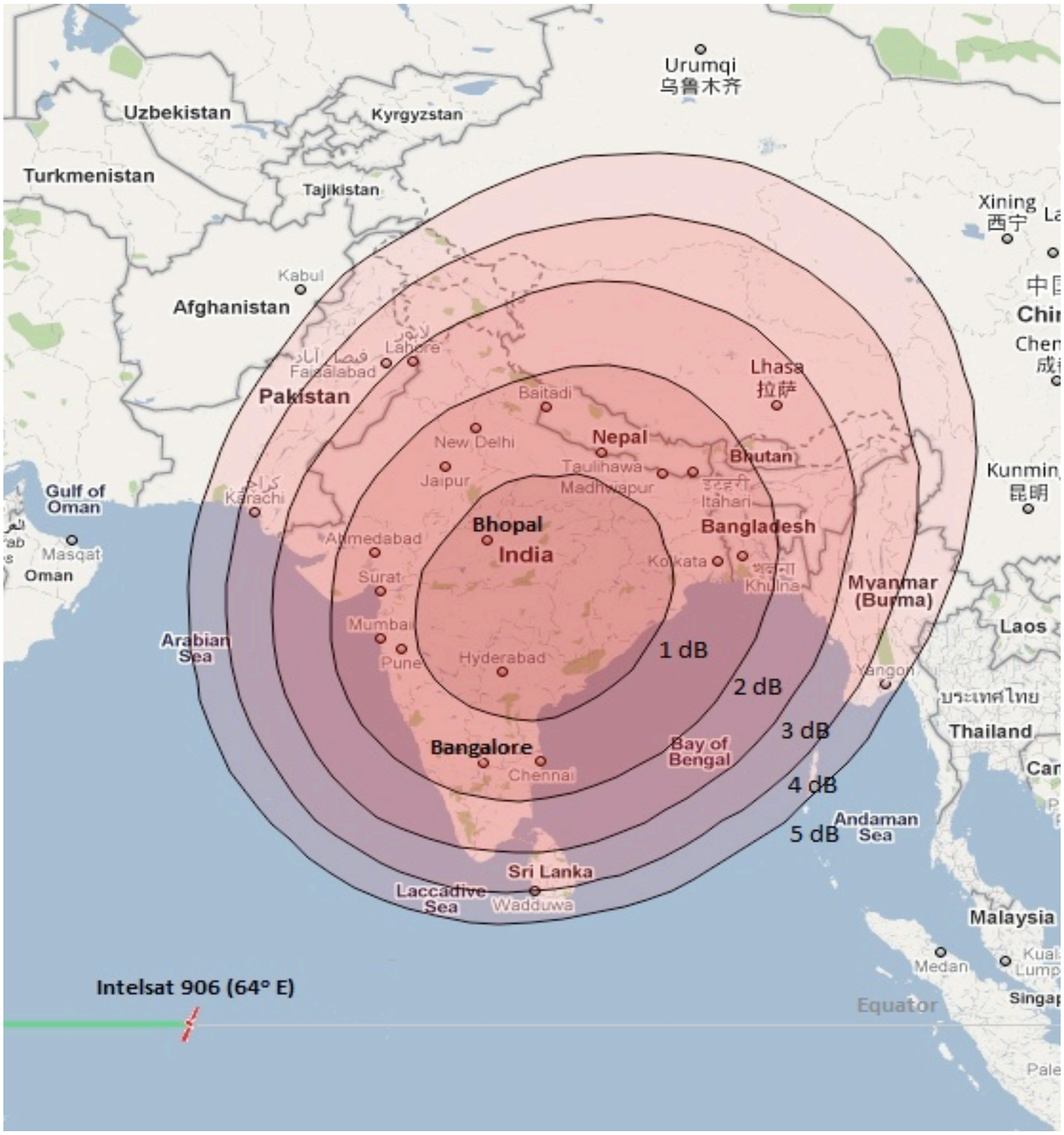


Fig. 4.1: Footprint of Intelsat-906 Spot Beam 2 over the Indian subcontinent. Based on data from [20]

4.5 Satellite Tracking and Visibility

The selected satellite Intelsat 906 is currently in stable geostationary orbit, kept at the correct longitude and inclination by repeated station-keeping maneuvers. However, when the satellite is used to provide low-cost Internet access, it will have exhausted a considerable percentage of fuel onboard and hence it will be possible to perform only east-west maneuvers, not the north-south maneuvers. As a result, the satellite will slowly drift into an inclined orbit. For the purpose of this project, we will assume that Intelsat 906 is already in inclined orbit. With only limited station keeping, the orbit keeps getting more and more inclined at the rate of approximately 0.85^o per year.

When Intelsat 906 is in stable geostationary orbit at 64.5^o E, the antenna at the central hub station in Bangalore, located at 12^o 58' N, 77^o 38' E is pointed towards the satellite at a fixed look angle. The calculated values, looking up from a ground station located at these co-ordinates at an altitude of 914 meters above mean sea level are: elevation angle 68.45^o above horizon and azimuth angle 226.15^o relative to true north (227.99^o relative to magnetic north). However, as the satellite begins to orbit in an inclined orbit, the azimuth and elevation angles required to look at the satellite vary, and instead of being one constant value, now they can be defined as a range of values, in degrees, that vary with variation in inclination angle of the satellite. The values for antenna at the central hub station in Bangalore looking at satellite inclined at different angles were calculated using GEOPoint 3.02, a simulation software developed by Gunamoi Software and available for free downloads. [18] The calculated values are shown in Table 4.3. As the inclination of satellite from geostationary orbit keeps increasing, the range of corresponding azimuth and elevation angles also increases almost linearly. These variations are illustrated in Figure 4.2 and 4.3. Similarly, azimuth and elevation values can also be calculated for every village station, knowing its latitude, longitude and elevation above mean sea level.

Inclination Angle (deg)	Azimuth Range (deg)		Elevation Range (deg)	
	Maximum	Minimum	Maximum	Minimum
0	226.15	226.15	68.45	68.45
0.1	226.37	225.93	68.53	68.37
0.2	226.60	225.7	68.62	68.28
0.3	226.82	225.49	68.70	68.20
0.4	227.05	225.27	68.78	68.12
0.5	227.28	225.05	68.86	68.03
0.6	227.52	224.84	68.94	67.95
0.7	227.75	224.63	69.02	67.86
0.8	227.99	224.42	69.10	67.78
0.9	228.22	224.21	69.18	67.69
1	228.46	224.00	69.26	67.61

Table 4.3: Range of variation in azimuth and elevation angles of antenna pointing towards Intelsat 906 satellite with variation in inclination of satellite orbit.

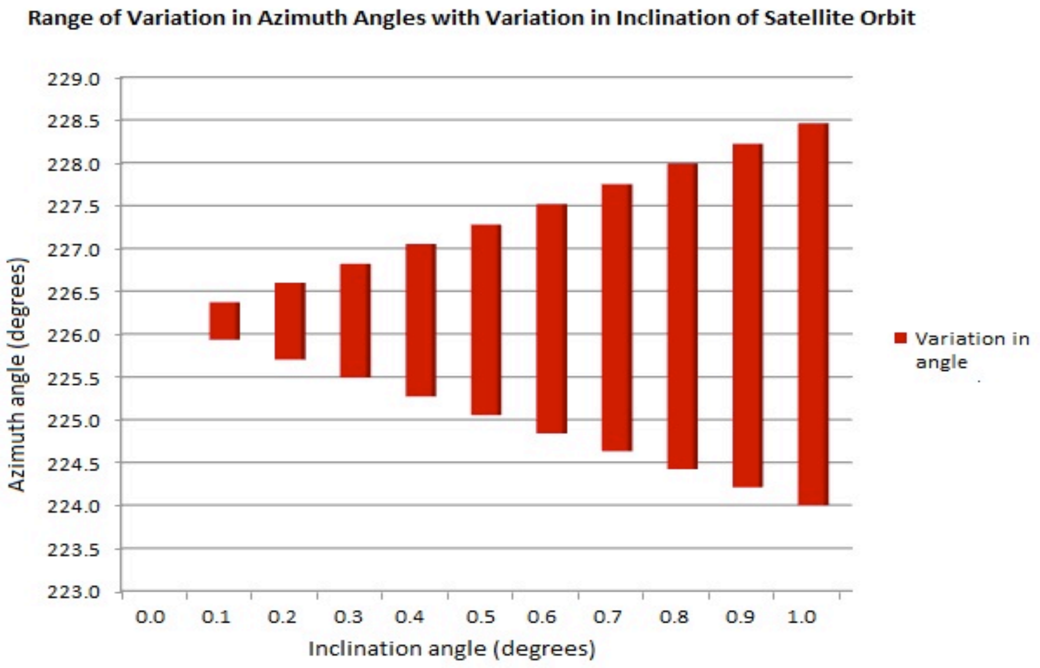


Fig 4.2: Variance of azimuth angles with variation in inclination of satellite orbit. Data from simulation using GEOPoint software

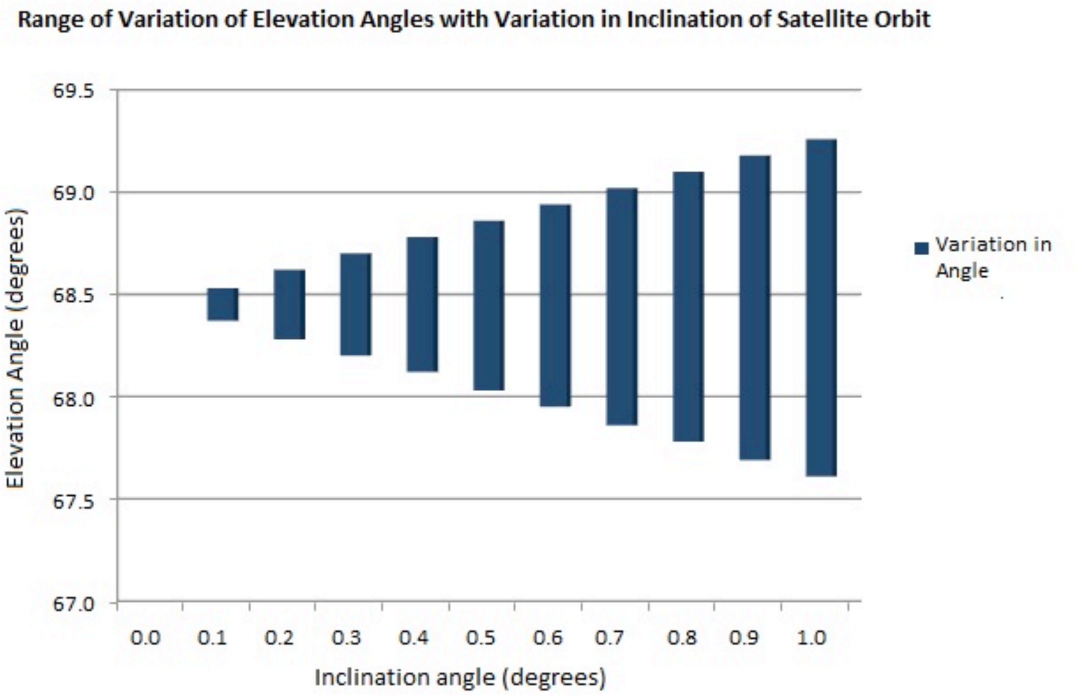


Fig 4.3: Variance of elevation angles with variation in inclination of satellite orbit. Data from simulation using GEOPoint software

4.6 Effect of Beamwidth and Antenna Gain

Since the satellite – Intelsat 906 is in inclined orbit, it traces a figure of eight pattern when observed from the earth. If the inclination of the satellite is known, the variation in azimuth and elevation angles required if the antenna is to always point towards the satellite can be calculated. It is a known fact that a geostationary satellite left without north-south station-keeping increases its inclination angle at an average rate of 0.85^o per year. As the satellite's inclination goes on increasing with passage of time, the size of the figure of eight it traces in the sky increases, and consequently the range of azimuth and elevation angles required for the earth station antenna to point to the satellite also increase. If the beamwidth of the earth station antenna is wide enough to cover the entire range of azimuth and elevation angles calculated for a particular inclination, it is ensured that the satellite always remains visible to the ground station without the need for any movement of the antenna. However, if the variation in azimuth or elevation is greater than the beamwidth of the antenna, the earth station will be able to see the satellite for only a certain part of the day, resulting in outage for the remaining time of the day. This situation is illustrated in Figure 4.4. The available beamwidth of the earth station is given by θ_a. The beamwidth required to cover the entire area of satellite movement in orbit is given by θ_r. If $\theta_a \geq \theta_r$, the satellite will always be visible to the earth station. If $\theta_a < \theta_r$, the satellite will be visible to the earth station only for the duration of time it takes to travel from point A to B and from point C to D shown in the figure and for the remaining time there will be signal outage. The period of outage depends on the value of $\Delta\theta$ – the difference between θ_a and θ_r.

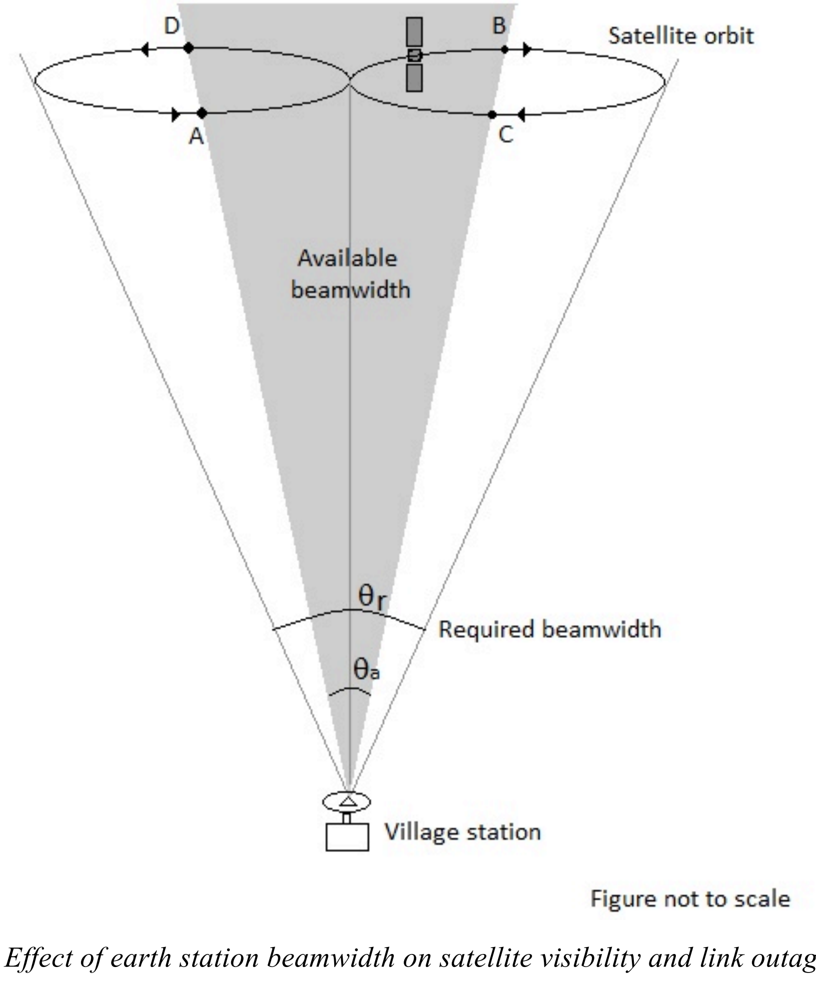


Fig 4.4: Effect of earth station beamwidth on satellite visibility and link outage

The apparent motion of the satellite about a nominal position as viewed from the center of the earth is a figure eight pattern. The height of the figure of eight in the north-south direction (h_{n-s}) and the width of the figure of eight (h_{e-w}) in east-west direction are described by the following equations - [35]

$$h_{n-s} = (2i) \text{ degrees} \qquad \ldots(4.2)$$

$$h_{e-w} = (i^2 / 115) \text{ degrees} \qquad \ldots(4.3)$$

where i is the inclination of the satellite's orbital plane with respect to the earth's equatorial plane in degrees. Using Equation 4.2 and 4.3, we can determine the height and width of the figure of eight over a period of time as the satellite inclination gradually increases. The calculated values are given in Table 4.4.

Period (years)	**Inclination (degrees)**	**h_{n-s} (degrees)**	**h_{e-w} (degrees)**
1.0	0.75	1.50	0.005
1.5	1.13	2.26	0.011
2.0	1.5	3.00	0.019
2.5	1.88	3.76	0.031
3.0	2.25	4.50	0.044
3.5	2.63	5.26	0.060
4.0	3.00	6.00	0.078
4.5	3.38	6.76	0.099
5.0	3.75	7.50	0.122

Table 4.4: Variation in height and width of figure of eight made by Intelsat-906 in inclined orbit with variation in angle of inclination

It is evident from Table 4.4 that the figure of eight pattern formed by the satellite in inclined orbit is much larger in the north-south direction than it is in the east-west direction. As a result, a village station antenna that has a beamwidth equal to or greater than h_{n-s} will always have the satellite visible in spite of the satellite not being geostationary. Considering this, if it is desired that the earth station be able to see the satellite for a longer period of time, it is necessary to design the earth station antenna with a wide beamwidth so that it can cover the increasing variation in satellite path with passage of time. The antenna beamwidth, antenna gain and antenna diameter are all related to each other. Antenna gain is inversely proportional to beamwidth. The approximate relation between the gain in linear units (G) and beamwidth in degrees (θ) of the antenna is given by [10]

$$G = \frac{33000}{\theta^2} \qquad \ldots(4.4)$$

This means that as we increase the beamwidth of the antenna, the gain of the antenna goes down. Since seeing the satellite requires increasing beamwidth with passage of time, consequently the antenna gain keeps decreasing and as a result the antenna diameter required to achieve the gain also keeps decreasing. This adversely affects the link performance by reducing the signal to noise ratio at the receiver. So, it is not possible to increase the antenna beamwidth indefinitely. Antenna gain is also directly proportional to the square of antenna diameter. Any change in one of these three parameters affects the other two. As a result, a tradeoff is required to determine the ideal beamwidth of the earth station antenna to ensure reasonably good satellite visibility and antenna gain. The antenna diameters required to maintain beamwidth necessary to ensure the satellite is within the antenna beamwidth as the inclination of its orbit increases over time are calculated and the results are shown in Table 4.5.

Time (years)	Inclination Of orbit (degrees)	Antenna beamwidth (degrees)	Antenna gain (dB)	Required diameter at 14 GHz (meters)	Required diameter at 11 GHz (meters)
1.0	0.75	1.5	41.7	1.02	1.30
1.5	1.13	2.26	38.1	0.68	0.86
2.0	1.50	3	35.6	0.51	0.65
2.5	1.88	3.76	33.7	0.41	0.52
3.0	2.25	4.5	32.1	0.34	0.43
3.5	2.63	5.26	30.7	0.29	0.37
4.0	3.00	6	29.6	0.25	0.32
4.5	3.38	6.76	28.6	0.23	0.29
5.0	3.75	7.5	27.7	0.20	0.26

Table 4.5: Variation in required beamwidth, antenna gain and resultant antenna diameters with change in inclination of satellite orbit over time.

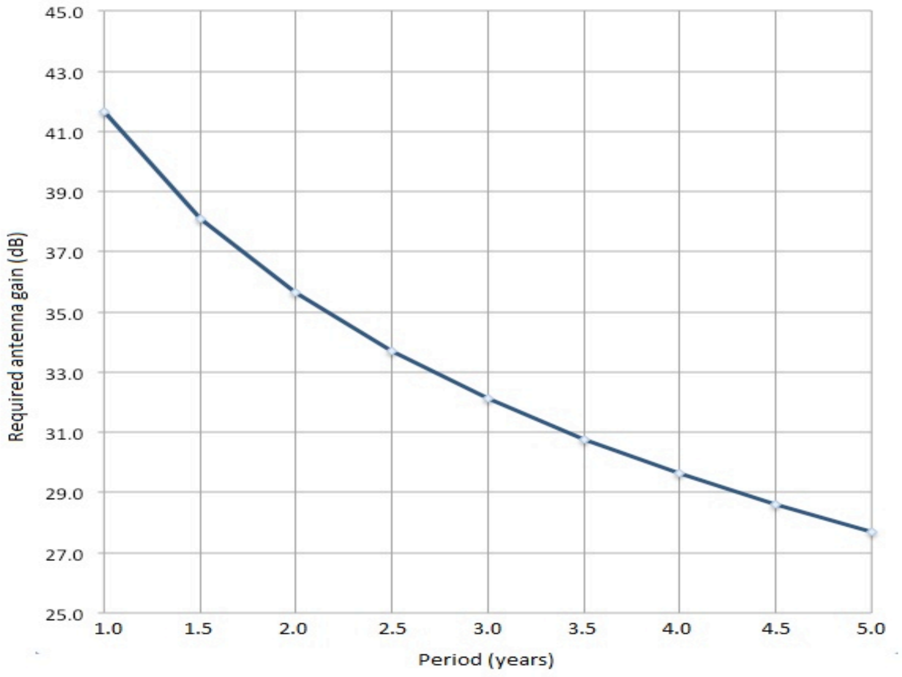


Fig 4.5: Reduction in antenna gain required to maintain adequate beamwidth to see the satellite over a period of time

As seen in the figure above, if the antenna is to have continuous view of Intelsat 906 in inclined orbit, it is necessary to decrease the antenna gain at regular intervals of time. This requires reduction in antenna size. It is possible to reduce the antenna dimensions by simply covering a part of the dish with non-radiating material. However, the area of dish required to be covered every time the dimension is varied needs to be calculated and skillfully implemented. This may not be possible to do at every village station since many of the stations would be located in remote areas with insufficient skilled labor. As a result, this option of using a fixed antenna with shrinking aperture is not feasible and it is necessary to look at other alternatives.

The alternative to avoid this problem is to equip the village station antenna with a stepper-motor based antenna controller, which is pre-programmed at installation so that it moves the antenna by a fixed amount after fixed intervals of time, and thus approximately tracks the motion of the satellite in one plane. When seen from the earth station, the satellite orbit is making a narrow figure of eight that is normal to the GEO arc, centered on the GEO arc. The figure of eight pattern as seen by the receiving antenna at a village station at 12^o 58’ N, 77^o 38’ E along with the GEO arc is shown in Figure 4.6 as an example. The motion of the satellite is periodic, which means that the figure of eight pattern repeats itself. The period of the motion is 23 hours, 56 minutes, and 4 seconds, which is also referred to as one sidereal day. Figure 4.6 shows that the apparent motion of the satellite is practically a straight line oriented in a direction perpendicular to the arc of satellites. The antenna controller uses this knowledge of the satellite’s apparent motion. If the antenna is on a polar mount, the variation takes place mostly in the plane orthogonal to the polar mount – the equivalent of elevation angle for an Az-El mount. In this case, it is not necessary to track on the polar axis for the first several years.

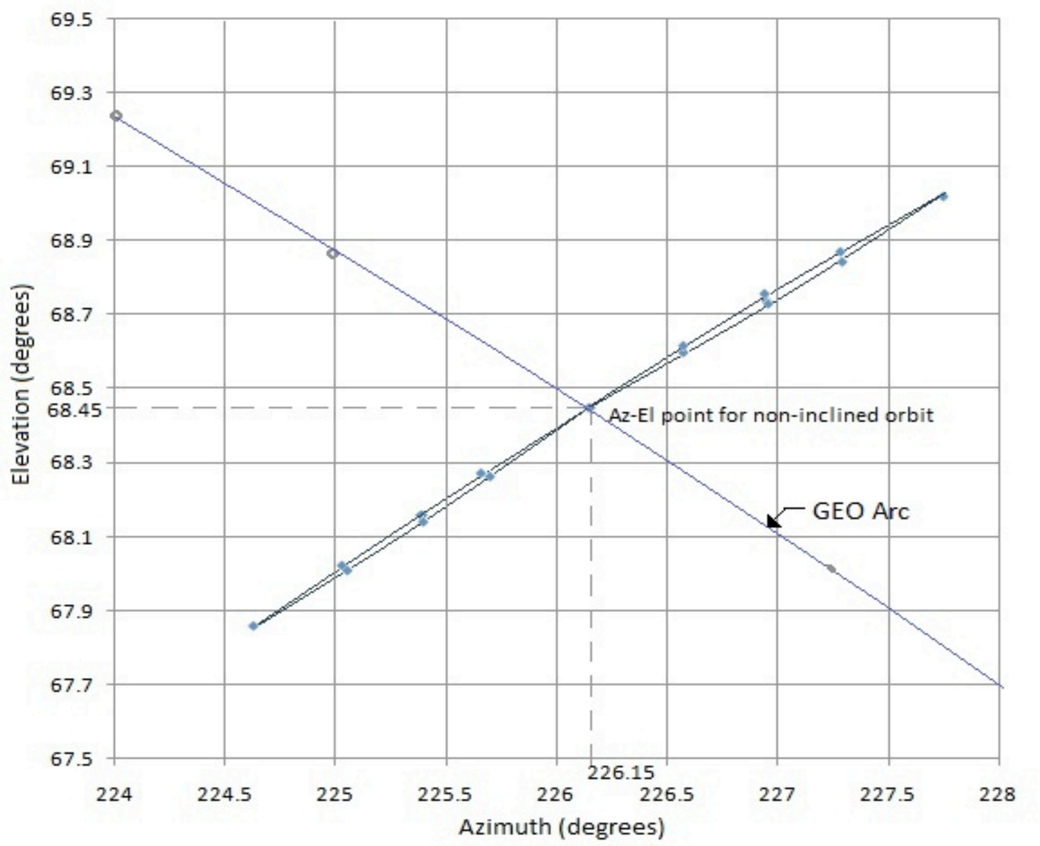


Fig. 4.6: Track of Intelsat-906 in an orbit inclined at 0.7^o to the GEO orbit over one sidereal day, as seen from a village station located at 12^o 58' N, 77^o 38' E. Drawn using data from [18]

Several AGC-controlled inclined orbit tracking satellite antenna controllers are available commercially. RC3000 Antenna Controller manufactured by Research Concepts Inc. [35] is one example of such a controller capable of tracking Intelsat 906 in inclined GEO orbit. The tracking controller moves the antenna automatically to track the satellite. This type of controller monitors the level of the received signal and moves the antenna periodically to maximize the signal. Most AGC-controlled controllers are equipped to maintain a history of the figure of eight pattern. The history is established during the first day's operation; thereafter, the history is used in two ways - it tells the controller which way to move the antenna when maximizing the signal, and it allows the controller to continue tracking if the satellite signal fails. The controller updates the history during the course of normal tracking. Thus, it responds automatically to changes in the shape of the tracking pattern as the satellite continues to drift along its north-south axis without the need for manual intervention, which makes it suitable for installation in village stations.

In case the tracking antenna controller at the village station develops a technical snag and stops moving the antenna in accordance with the motion of the satellite, the antenna will become stationary, pointing at any point on the figure of eight. In this case, the satellite, Intelsat 906 will still cross the point in orbit towards which the antenna is pointing twice every sidereal day. For the duration when the satellite crosses the main lobe of the antenna beam, the village station will receive Internet service. This saves the village from suffering a total communications blackout during the time it takes to dispatch technicians to the remote location to repair the malfunctioning controller.

4.7 Interference with Adjacent Satellites

When this system is implemented, the satellite being used- Intelsat 906 will be a relatively elderly satellite and although it is in a slightly inclined orbit, it will occupy a slot in the GEO orbit. The GEO orbit is the most economically lucrative satellite orbit around the earth and satellite orbital slots on GEO orbit are very expensive. As a result, every corporation would prefer to use the GEO orbital slot procured by it to install a modern high capacity satellite serving a much larger number of more wealthy corporations or customers instead of using it to provide a rural Internet service with relatively little income. Apart from occupying the slot, it will also lock up some part of the frequency band at that location. These factors may make it difficult to gain access to an exclusive GEO slot and suitable frequencies for the proposed project. One approach to overcome this problem is to study the possibility of placing the satellite midway between two allocated orbital slots – typically one degree from another GEO satellite on each side and sharing frequencies with these satellites. The satellite being used for our project must be switched off, and the uplink transmitters must cease to transmit when interference to the adjacent GEO satellites exceed a specified threshold.

If the uplink transmitting antennas are kept reasonably large, measuring approximately 2.5 to 3 m in diameter, and they track the satellite in one plane using a controller as explained in the previous section, it should be possible to operate within 1.5 or 2 degrees of the adjacent satellites. Since the motion of the inclined orbit satellite is sinusoidal, most of its time is spent at the extremes of the figure of eight loop the satellite makes every sidereal day. The power pattern of a circular aperture antenna depends upon the transmitting frequency and the antenna diameter. For a village station antenna with diameter 2 meters, transmitting at 14 GHz, the 3-dB beamwidth is 0.8^o and the first side lobe is located 0.6^o off axis where the signal level is 17.5 dB down from the peak value. [19] If it is possible to place the adjacent satellites in the side lobes of the uplink pattern of the central hub antenna, it may not be required to cease transmission for much of the time. Using Equation 4.5, it is possible to calculate the width of the main lobe and use the information to determine the time for which the transmitter must be shut down to achieve a specific level of interference.

The amount of time for which uploads need to be suspended depends on the time taken by Intelsat 906 to travel the path on its figure of eight that lies in the vicinity of adjacent GEO satellite. This time can be determined from the angle of inclination of Intelsat 906 at a given time from the GEO orbit. If Intelsat 906 is orbiting in an orbit inclined by 1^o from the GEO plane, starting from the equatorial plane and moving north, it reaches 0.5^o north of the GEO plane after 2 hours, 0.866^o north after 4 hours and at its extreme point 1^o north after 6 hours. If it is determined that the interference to adjacent satellites is greater than accepted threshold when Intelsat 906 is within 0.5^o of their slot in GEO orbit, it would be required to shut down the uplink transmission to Intelsat 906 for a period of four hours, twice per day.

There have been various proposals to put several satellites into the same inclined orbit so that they chase one another round the figure of eight as one way to increase GEO capacity. In this case, the satellites are placed deliberately in an inclined orbit with significant inclination, usually greater than 5^o from the GEO orbit. Satellites crossing the GEO arc can be turned off and the earth station transmitters silenced for a short period of time if the need be, and the earth station antennas can divert transmission to the other satellites. This is one way to increase capacity and avoid possible interference problems near the GEO arc by the system being proposed in this thesis. Procuring multiple communication satellites, all of them nearing their end of scheduled life and maintaining them in a precise inclined orbit increases the installation and operating cost significantly and is not feasible on a low-cost system being proposed here. However, a staggered approach can be used to implement this variation. Over a period of eight years, the first satellite launched for the proposed project will be inclined at an angle of 6^{o} from the GEO orbit. At this point, a second communication satellite can be moved to the GEO slot and allowed to drift into inclined orbit. Depending on the orbital paths of both satellites, a time-sharing schedule can be worked out to switch off transmission to either of the satellites when they are in proximity of adjacent satellites in GEO orbit.

Chapter 5

Infrastructure and System Components

The proposed system is based on a modified hub-and-spoke topology. For this project, one central hub will be located in a convenient urban location in the city of Bangalore, acting as the ISP backend and networks operation center connecting the system to the Internet backbone. The central hub also connects via multiple data channels to the satellite in slightly inclined geostationary orbit to provide satellite Internet links to village hubs. Each village hub acts as a Wi-Fi hotspot to provide last mile connectivity wirelessly. Thus, the system topology is a double-star – the central NOC and the village hubs form the inner star and the village hub and customers form the outer star. This double-star topology is shown in Figure 5.1.

In this system, connection to the Internet is achieved by the following procedure - the customer sends a connection request in the form of a data packet to the village station via Wi-Fi link. The village hub forwards this request to the central hub station via the satellite. The packet contains a station ID describing its location. The central hub station decodes the request and notes the location of the requesting village station. The connection between the Internet and the village hub is established through an Internet Service Provider (ISP). A response from the ISP is sent back to the customer using the satellite and the local Wi-Fi link. The links between the ISP and the customer in this system are highly asymmetric. The customer can send only short requests at a low data rate. The ISP then dumps data to the customer at a high data rate. This mode of operation suits applications where the customer is browsing the Internet for information, or is requesting large files or video frames from the Internet. It works less well for sending large files from the customer to the Internet. However, most Internet access systems utilize asymmetry in this way.

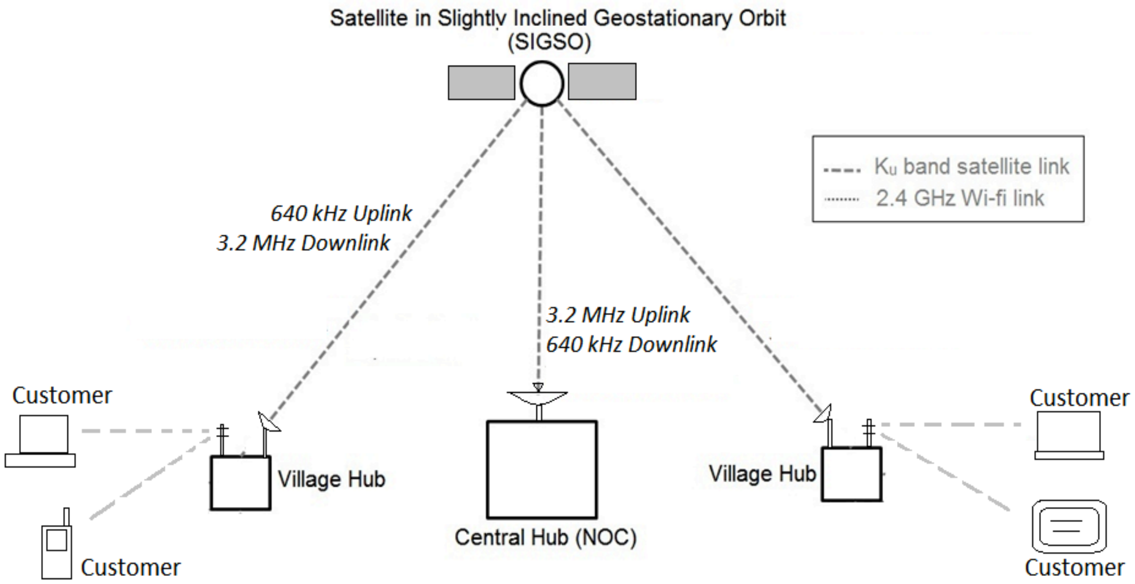


Fig 5.1: Block diagram of System Components Overview

5.1 Central Hub and ISP Backbone

An Internet service provider (ISP) is a company that offers its customers access to the Internet using a data transmission technology appropriate for delivering Internet Protocol packets or frames, such as dial-up, DSL, cable modem, wireless or dedicated high-speed interconnects. For users and small businesses, the most popular options include dial-up, DSL (typically Asymmetric Digital Subscriber Line, ADSL), broadband wireless, cable modem, fiber to the premises (FTTH), and Integrated Services Digital Network (ISDN). For customers with more demanding requirements, such as medium-to-large businesses, Ethernet, Metro Ethernet, Gigabit Ethernet, Frame Relay, ISDN (BRI or PRI), ATM, satellite Internet access and synchronous optical networking (SONET) are more likely to be used.

While most Internet links are designed with higher downlink bandwidth than uplink bandwidth, the link between central hub and the satellite needs higher uplink bandwidth than downlink bandwidth, since the data traffic to be sent to customers, constituting of downloads at the customer end, is expected to be greater than the data traffic received from the customers, which would be uploads and webpage requests from the customers. The central hub has a high power requirement and a large antenna is required to be installed at the premises, which would enable transmission and reception of several channels of data traffic. The central hub acts as a network operations center (NOC) transporting data back and forth from the hundreds of village hubs connected in a star topology. The size of antenna, power requirements and maximum achievable data rates from the central hub will be calculated in the next chapter.

The major components of the transmitting and receiving portion of the central hub station are shown in Figures 5.2 and 5.3 respectively. The uplink from the central hub to the satellite is an FDMA-TDM link. Internet data coming from ISP and heading to each transponder on board Intelsat 906 is divided into ten channels, each 3.2 MHz wide. Each channel is further divided into twenty time slots and each slot carries data bound for a different village station. By implementing this multiplexing 200 village stations can be serviced using each transponder onboard the satellite. Packaging the data from the ISP into this format is accomplished at the central hub. Similarly, on the downlink the central hub receives data from village stations packaged in twenty time slots in each 640 kHz wide channel. This data is extracted, demodulated and re-packaged by the central hub to be sent to the ISP.

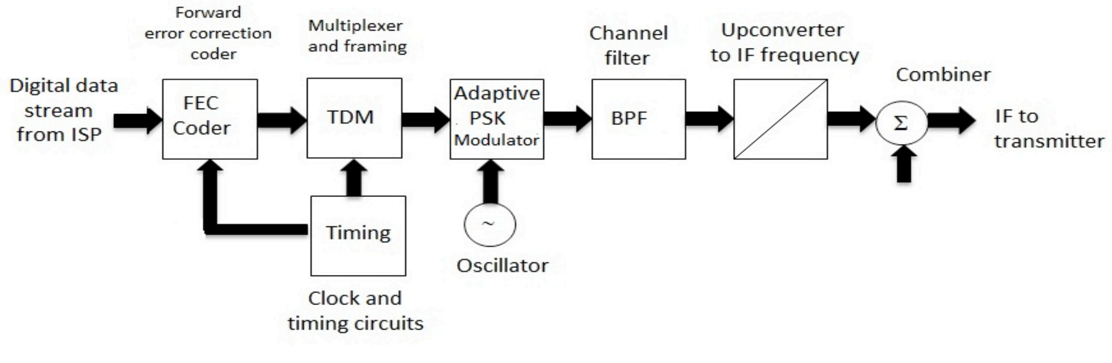


Fig 5.2: Uplink equipment for transmitting portion of digital central hub. Based on data from[10]

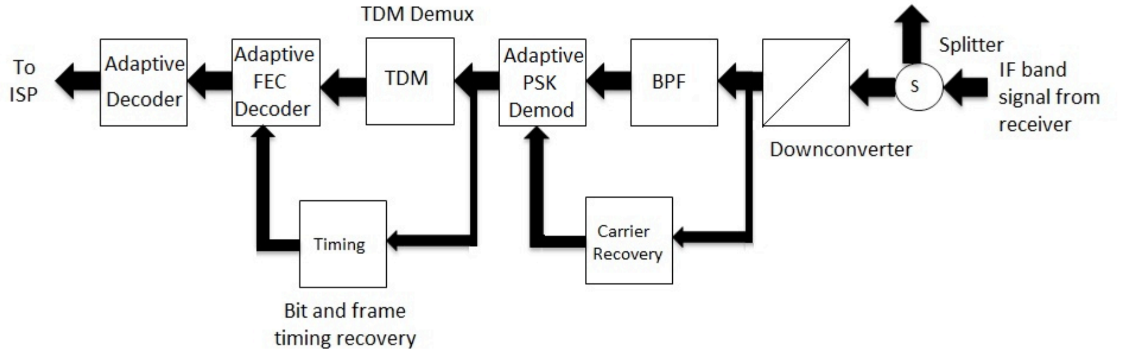


Fig 5.3: Downlink equipment for digital central hub. Based on data from[10]

5.2 Satellite Transponders

The satellite being used for this project – Intelsat 906 is equipped with 24 Ku band bent-pipe transponders, each having a 36 MHz bandwidth. [20] Transponders for use in the 14/11 GHz frequency range (Ku band) employ a double frequency conversion scheme as it is easier to design filters, amplifiers and equalizers operating at an intermediate frequency (IF) such as 1100 MHz than 14 GHz or 11 GHz. Figure 5.4 shows the major components of a typical double conversion bent-pipe transponder used on Intelsat satellites for 14/11 GHz operations. The output power amplifier is a travelling wave tube amplifier since the output power available on Intelsat 906 is very high, saturating around 100 W. The first local oscillator operates at 13 GHz to provide frequency shift to intermediate frequency (IF). The band pass filter after the mixer removes unwanted signals generated by the down-conversion. The second local oscillator operates at 10 GHz to provide upconversion from IF to Ku band downlink frequency. The gain of the transponder can be set via uplink command system from the ground station. Each transponder has built-in redundancy for high-power amplifier (HPA) in the form of a spare TWT amplifier that can be switched into circuit if the primary amplifier fails. Since HPAs usually have limited lifetime representing the least reliable component in most transponders, this redundancy greatly increases the probability that the satellite remains operational even after its scheduled end of life, a criterion critical for the success of the proposed low-cost Internet system.

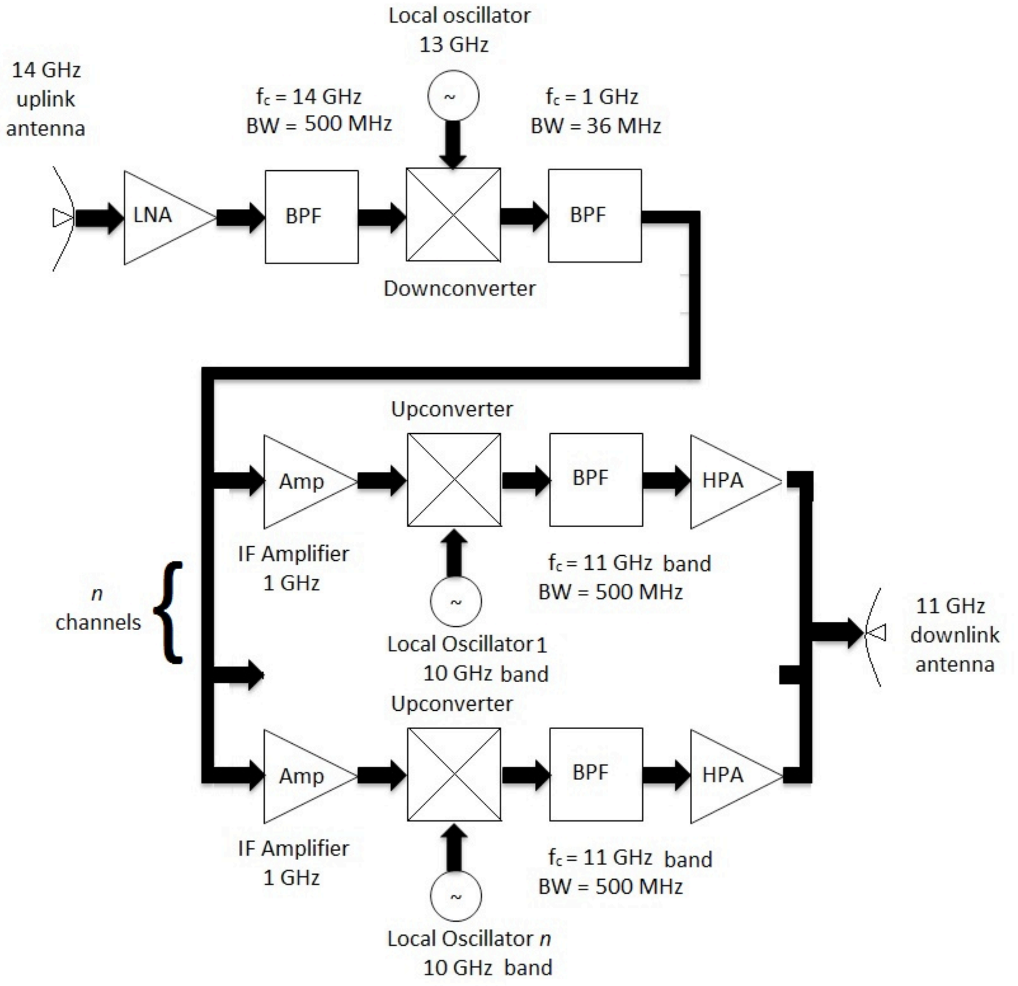


Fig. 5.4: Simplified block diagram of double conversion bent-pipe transponder onboard Intelsat 906 for 14/11 GHz operation. Based on data from [10]

5.3 Village Hub Terminals

Every village covered by the proposed system to provide Internet access will have one village hub terminal. The village hub terminal design is a VSAT. A Very Small Aperture Terminal (VSAT) is a two-way satellite ground station with a dish antenna that is smaller than 3 meters. The majority of VSAT antennas range from 75 cm to 2.5 m. VSATs access satellites in geosynchronous orbit to relay data from small remote earth stations called terminals to a master earth station called the network operations center (NOC) in star configurations. To keep costs low, village hubs will use commercially available VSAT parabolic dish antennas with diameter 2.0 meters.

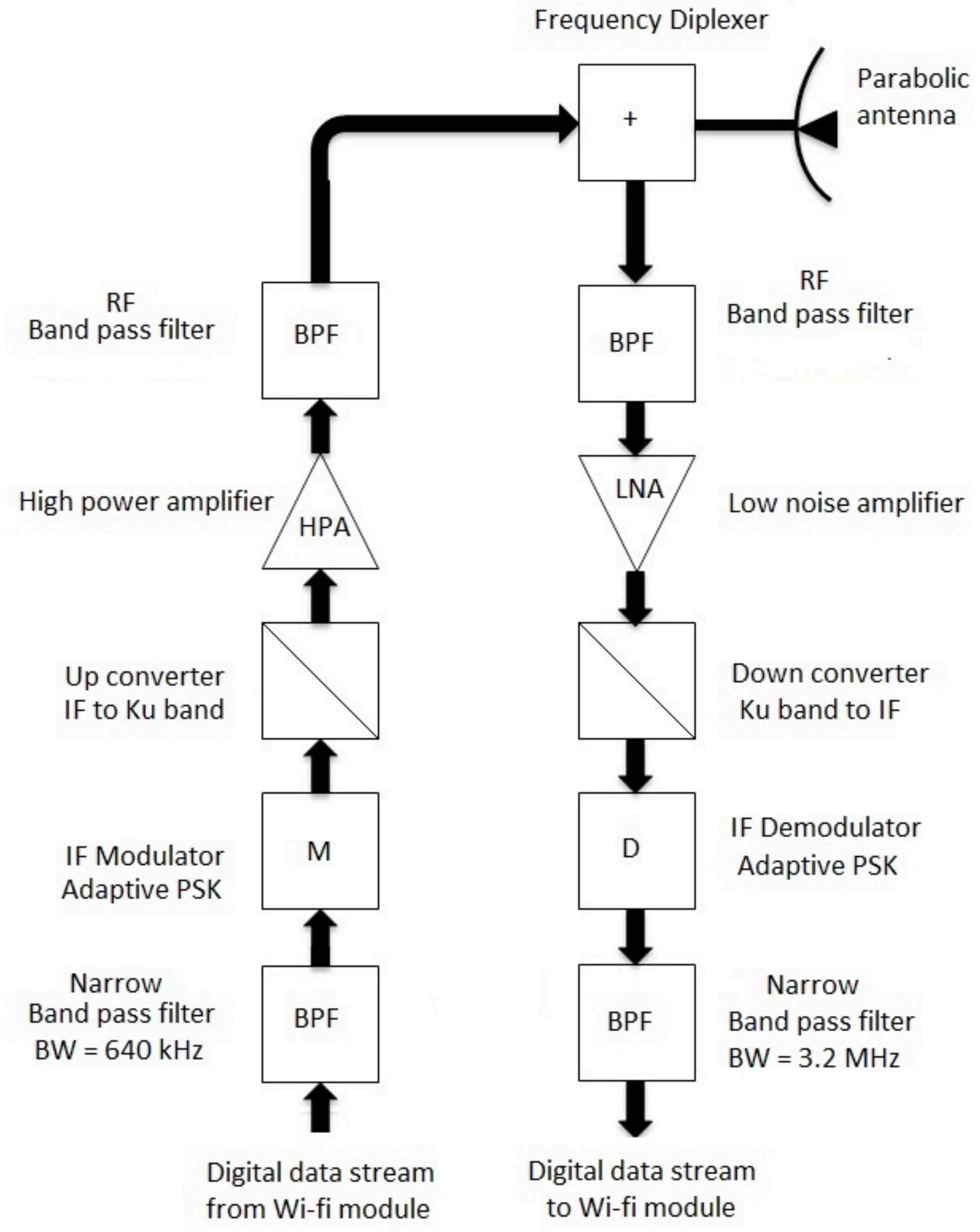


Fig 5.5: Village hub components block diagram. Based on data from [13]

The major component blocks of the village hub have been illustrated in Figure 5.5. The major RF components include a low noise amplifier (LNA) of the receiver and a high power amplifier (HPA) of the transmitter, up and down converters to translate signals between Ku band RF frequencies and UHF band intermediate frequencies, an orthomode transducer (OMT) used either to combine or to separate the uplink and downlink signals transmitted over the same waveguide and an Indoor unit (IDU) housing the Internet modem and other electrical devices. The village hub receives a data stream from the NOC at the central hub via the satellite. On the other hand, the village hub itself also acts as a local NOC, distributing the data stream among customers in a village wirelessly using IEEE 802.11n Wi-Fi protocol. For this purpose, the village hub contains a Wi-Fi router and an antenna to transmit an Internet data stream using the 2.4 GHz band. Since the transmission between the village hub and satellite is carried out in K_u band in the range of 11 to 14 GHz, there is no interference of this signal with the Wi-Fi signals transmitted from the same physical location.

The components used in the village station need to provide reliable data communication link meeting the specified quality of service, but at the same time it is also necessary to keep the cost of equipment as low as possible, considering these equipment are required in large numbers across the system. The amplifier on the receiver side is required to have a very low noise temperature. Cryogenically cooled parametric amplifiers with liquid helium cooling can achieve noise temperatures as low as 40 K but it is expensive to install and maintain them. As a result, GaAsFET amplifiers that require no cooling and capable of achieving noise temperature in the range of 100 K are used. On the transmit channel, solid-state high-power amplifiers (HPA) are deployed because they do not require the very high voltages needed by TWT and klystron amplifiers.

The village hubs are set up in remote rural areas with no reliable electricity supply. As a result, care must be taken during design to keep power requirement of the village hub as low as possible. This forms the upper bound for maximum data rate achievable. Most parts of India lie in the tropical climate zone and receive abundant sunlight for most of the year. In order to take advantage of this, solar panels with photovoltaic cells are set up at each village hub to provide most of the energy requirement of the hub. A pedal powered generator can be included for emergency power backup.

5.4 Wi-Fi System Blocks

The project proposes last mile connectivity from village station to customers using IEEE 802.11 g/n to create a wireless local area network. The 802.11 family consists of a series of over-the-air modulation techniques that use the same basic protocol. 802.11g uses the 2.4 GHz ISM band, which is also used by other consumer devices. As a result, it may occasionally suffer interference from microwave ovens, cordless phones and Bluetooth devices. 802.11g devices control their interference and susceptibility to interference by using orthogonal frequency-division multiplexing (OFDM) signaling. The segment of the radio frequency spectrum used by 802.11 varies between countries. In the United States, 802.11g devices may be operated without a license, as allowed in Part 15 of the FCC Rules and Regulations. Frequencies used by channels one through six of 802.11b and 802.11g fall within the 2.4 GHz ISM unlicensed band. 802.11n is an amendment that improves upon the previous 802.11 standards by adding multiple-input multiple-output antennas (MIMO). 802.11n operates on both the 2.4 GHz and the lesser-used 5 GHz bands. In India, only the 802.11b/g working on 2.4 GHz frequency range has been opened for unlicensed use. The 5 GHz spectrum has not been opened for use since it coincides with the spectrum used by the police department. [21]

Internet connectivity from the village station to customers is provided by means of a wireless access point (WAP). It is a device that allows wireless devices to connect to the Internet using Wi-Fi, Bluetooth or related standards. A WAP connects a group of wireless devices to a network hub using a wireless adapter. A wireless adapter allows a device such as a laptop computer or mobile phone to connect to a wireless network. As of 2010, most newer laptop computers come equipped with in-built internal adapters. As a result no extra hardware is required to be purchased by the customers to access the Internet using the proposed satellite system. At the village station, the main hardware to be installed is a wireless router along with a range-extending antenna. As seen in Section 2.3, the villages in India have a compact layout, so an antenna array that has good vertical height and a narrow beam in the vertical plane with 360 degrees coverage in the horizontal plane can be located centrally in the village to provide coverage to the entire village area.

Wireless routers integrate a WAP, Ethernet switch and internal router firmware application that provides IP routing and DNS forwarding through an integrated WAN-interface. A wireless router allows wired and wireless Ethernet LAN devices to connect to a single WAN device, which for the proposed system is the village hub. The Internet data stream arriving via satellite link to a village station is demodulated to extract the digital bit stream. This bit stream consists of data packets encapsulated using the standard OSI model. This bit stream is fed to the wireless router. This effectively emulates the conventional design wherein the wireless router is connected to a wired broadband Internet service. So, no modifications are required to the commercially available wireless routers for use in the proposed system.

5.5 Selection of Modulation Scheme

While any parameter, or a combination of parameters – amplitude, frequency or phase may be digitally modulated; phase modulation is almost universally used for satellites. Digital phase modulation is also called phase shift keying (PSK). An *m*-phase PSK modulator assigns the phase of the carrier one of *m* states according to the value of the modulating voltage. A two-phase PSK is usually called BPSK while a four-phase or quadriphase PSK is known as QPSK. Several newer satellite systems use 8-PSK where the phase of the carrier is assigned one of eight pre-decided states. The stream of incoming bits determines which of the *m* available symbols will be transmitted. The relationship between number of bits required to specify which of *m* possible symbols is being transmitted is given by

$$N_b = \log_2 m \qquad \ldots(5.1)$$

where N_b is the number of bits per symbol. In 8-PSK, $m = 8$. Hence, number of bits per symbol, $N_b = 3$.

Apart from individual keying based schemes, another popular modulation scheme is quadrature amplitude modulation (QAM). It conveys two digital bit streams by modulating the amplitudes of two carrier waves, using ASK. These two waves, usually sinusoids, are out of phase with each other by 90° and are thus called quadrature carriers. The modulated waves are summed and the resulting waveform is a combination of both PSK and ASK. In the digital QAM case, a finite number of at least two phases, and at least two amplitudes are used. QPSK can be considered as a special case of QAM where the magnitude of modulation signal is constant. Higher order QAM schemes are not preferred for satellite communication links since reduced noise immunity due to small constellation separation makes it difficult to achieve theoretical performance thresholds. Selection of a modulation scheme involves considerations in terms of bandwidth efficiency and energy efficiency.

5.6 Bit Error Rates and Channel Capacity

The bit error rates depend on the type of modulation scheme used. A comparison of the required E_b/N_o values required to achieve a particular bit error rate while using different phase shift keying modulation schemes is illustrated in Figure 5.6. As seen in the figure, QPSK modulated channel requires an E_b/N_o value that is almost 3 dB less than the corresponding value required for an 8-PSK modulated channel to achieve the same bit error rate. In general, higher order PSK modulations require correspondingly higher E_b/N_o values to achieve the same bit error rates. Considering this, ideally QPSK modulation should be selected to be implemented on the satellite link for this project. However, the data rate achieved by using QPSK is relatively low. So, a tradeoff is made between data rate and E_b/N_0 required to achieve the desired bit error. This is achieved in the proposed system using adaptive modulation. In clear air, the preferred modulation on satellite links is 8-PSK. However, when it rains on a link and the CNR on the link goes down, it becomes necessary to change over to a lower order modulation scheme such as QPSK, which can achieve similar BER at 3 dB lower E_b/N_o than 8-PSK as shown in Figure 5.6.

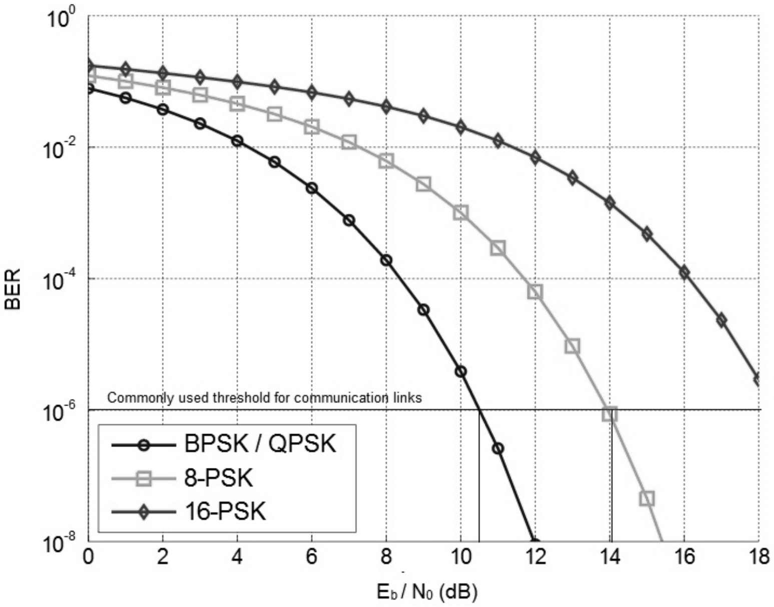


Fig 5.6: Bit error rate (BER) comparison for various phase shift keying modulation schemes. . Diagram based on data from [38]

Any communication channel operating over a noisy channel has an upper limit on the information carrying capacity known as the Shannon bound. Figure 5.7 shows a comparison of some of the commonly used modulation schemes showing their relative position with respect to the Shannon bound. The preferred modulation scheme used for the satellite link for this project is 8-PSK, which lies approximately at the center of the figure, implying a balanced tradeoff between spectral efficiency and energy efficiency.

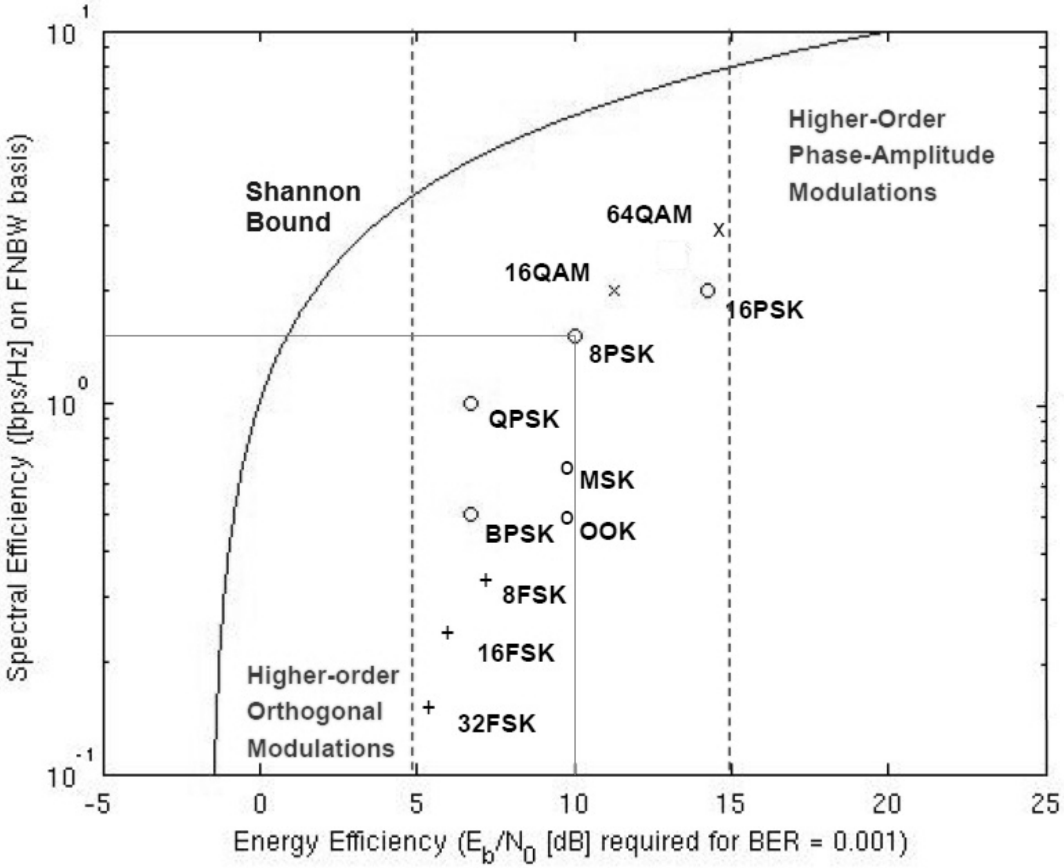


Fig 5.7: Comparison of spectral efficiency and energy efficiency of various modulation schemes with respect to Shannon bound. Diagram based on data from [38]

For 8-PSK, the relation between probability of bit error P_e and E_b/N_o is given by

$$P_b = Q\left(\sqrt{\frac{0.88E_b}{N_o}}\right) \qquad \ldots(5.2)$$

Also, the relation between E_b/N_o and CNR is given by

$$CNR = \frac{r_b}{B}\frac{E_b}{N_o} \qquad \ldots(5.3)$$

where r_b is the channel data rate and B is the channel bandwidth. For 8-PSK, $r_b = 3B$. Using this information, we can calculate that the minimum CNR required to achieve a

BER of 10^{-6} on an 8-PSK channel, assuming ideal RRC filtering is 76.91 or 18.8 dB. However, since there are no ideal RRC filters in practice, an implementation margin is included in link budget calculations.

5.7 Forward Error Correction

In any digital communication system, it is possible to insert redundant bits into the data stream, which can notify when a bit error occurs. Systems that can only detect errors use error-detecting codes. Systems that can detect and correct errors use forward error correction (FEC). The two main categories of FEC codes are block codes and convolutional codes. Block codes work on fixed-size blocks of bits or symbols of predetermined size. Convolutional codes work on bit or symbol streams of arbitrary length. They are most often decoded with the Viterbi algorithm, though other algorithms are sometimes used. Most block codes were developed for error correction in early computer memories and subsequently applied to digital data transmission. Hamming codes and BCH codes are some of the widely used block codes.

The improvement in bit error rate by use of block encoding can be calculated by comparing uncoded error rate to that obtained after correction of blocks of encoded data. The (127, 113) BCH code is a double error-correcting code specified for use on Intelsat TDMA systems [10]. Use of this code for FEC gives a 6.0 dB improvement in the E_b/N_o required to achieve a BER of 10^{-6}. [23] Half rate FEC using convolutional decoding also gives a similar improvement. This is called the coding gain. In order to obtain coding gain, we must increase bit rate on the link, which results in lower E_b/N_o because the noise bandwidth has to be increased. In case of half rate FEC, if we double the noise bandwidth to transmit at the same data rate, the CNR ratio falls by 3.0 dB and the effective improvement due to FEC is only 3.0 dB. However, FEC is required to ensure correct Internet data stream reaches village stations over satellite link, irrespective of the amount of coding gain achieved in the process.

Forward error correction in the proposed system is implemented only on the satellite link. The central hub receives Internet data from the ISP encapsulated in standard Internet Protocol (IP) packets. The errors are corrected using standard Transmission Control Protocol (TCP) and the data stream is extracted. This data stream is transmitted over the satellite link after adding appropriate FEC depending on prevailing weather conditions. This process of changing protocols is called spoofing. The satellite transponders onboard Intelsat 906 being bent-pipe type, no error correction or detection is done at the end of uplink. The corrupted data stream is transmitted as downlink and at the village station, half rate convolutional decoder detects and corrects the errors, thereby providing error-free data stream. This data stream once again undergoes spoofing, and is now encapsulated into packets according to IEEE 802.11g or 802.11n protocol depending upon the size of the village being served. Both these protocols have their own FEC schemes, which are applied before the data stream is transmitted wirelessly to the customers. The various error correction protocols being used on different links in the proposed system are illustrated in Figure 5.8.

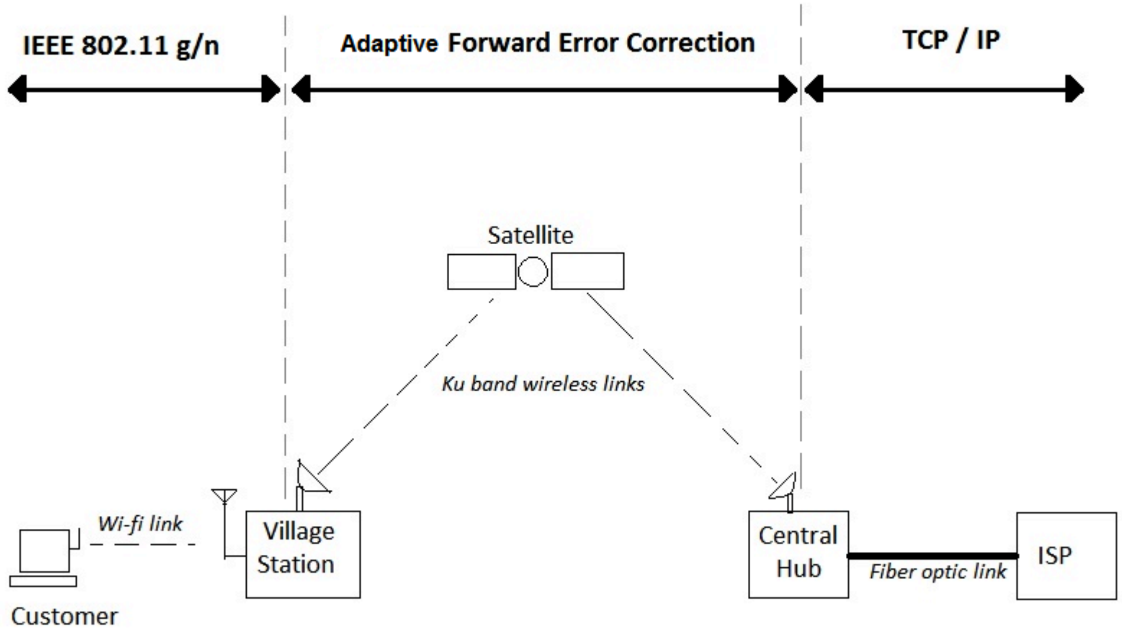


Fig 5.8: Error correction protocols used on different links of the satellite Internet project

Chapter 6
System Design And Link Budgets

This chapter focuses on quantitative analysis of the system using a Ku-band satellite in inclined geosynchronous orbit to provide connection to the Internet from a village station. The analysis is in two parts. The first part establishes the design of the communications links and terminals. The second part examines the capacity of the satellite.

6.1 System Capacity

The satellite being used for the proposed system- Intelsat 906 is equipped with 24 Ku band transponders and 72 C band transponders. The total available bandwidth on each transponder is 36 MHz. In order to provide Internet access to multiple villages at the same time using a single transponder, this available bandwidth is divided into multiple channels. Since the inbound channels would be used mostly to request webpages and send emails while the outbound channels would be used to transfer webpages, including images and video, the data rate on inbound channels is kept lower than the data rate on outbound channels. This is achieved by dividing each transponder bandwidth of 36 MHz into 50 channels of 640 kHz each with 80 kHz guard bands between channels on the transponders used for inbound link. On the outbound link, each transponder bandwidth of 36 MHz is divided into 10 channels, each of 3.2 MHz with 400 kHz guard bands between channels. Further, each channel is divided into 24 TDM slots, with each timeslot carrying data traffic for one village station.

Since the outbound links are operated at a data rate five times the inbound links, each outbound channel occupies five times the bandwidth occupied by each inbound channel. The total available bandwidth on Intelsat 906 is accordingly divided to get an equal number of inbound and outbound channels. Out of the 24 Ku band transponders, 20 transponders are assigned to carry outbound traffic with each transponder carrying 10 outbound channels, while 4 Ku band transponders carry inbound traffic with 50 inbound channels on each transponder. Thus, the system will have 200 Ku band channels. Since each FDM channel is to be divided into 24 TDM slots to serve 24 village stations, the 200 channels can serve 4,800 village stations if each slot is assigned exclusively to one village station. This is the simplest system configuration, but not necessarily the most optimum one. Depending on the results of link budgets, appropriate system optimization will be considered if possible.

6.2 Satellite Communication Links Setup

Any communication system is designed to meet certain minimum performance standards, usually limited by the amount of maximum permissible transmitted power and available bandwidth. The most important performance criterion is the signal-to-noise ratio (S/N) in the information channel. The S/N in a baseband channel depends mainly on the carrier-to-noise ratio (CNR) of the RF signal in the receiver, the type of modulation, and the IF and baseband bandwidths. In order to analyze link performance, we need to calculate the carrier power in the receiver and the noise power in the receiver, to establish the CNR. The link budgets that calculate these values are presented in this chapter.

The technical specifications for satellite transponder parameters are typical values for Intelsat-906. [24] The Ku band transponders onboard Intelsat-906 have transmitters operating at frequencies from 10.954 GHz to 11.191 GHz and 11.459 GHz to 11.693 GHz. The transmitters are fitted with travelling wave tube amplifiers (TWTAs) with maximum output power 100 W. The frequencies selected for link budget calculations are shown in Table 6.1.

In clear air, the free-space path loss (FSPL) is given by

$$FSPL = (\frac{4\pi d}{\lambda})^2 = (\frac{4\pi df}{c})^2 \qquad \ldots(6.1)$$

Here λ is the signal wavelength in meters; f is the signal frequency in Hz, d is the distance between satellite and earth station in meters and c is the speed of light in vacuum, a universal constant with value 2.99792458×10^8 m/s. According to this equation, FSPL for each of the four links under consideration is calculated for one village station and the results in decibel units are provided in Table 6.1. The actual path length d depends upon the geographic location of each village station and will be slightly different from the typical value of 35,768 km.

The total available bandwidth on each transponder is 36 MHz. In order to provide Internet access to multiple villages at the same time using a single transponder, this available bandwidth is divided into multiple channels. Since the inbound channels would be used mostly to request webpages and send emails while the outbound channels would be used to transfer webpages, including images and video, the data rate on inbound channels is kept lower than the data rate on outbound channels. This is achieved by dividing each transponder bandwidth of 36 MHz into 50 channels of 640 kHz each with a 80 kHz guard band between channels on the transponders used for inbound link. On the outbound link, each transponder bandwidth of 36 MHz is divided into 10 channels, each of 3.2 MHz with a 400 kHz guard band between channels.

The antenna gain for transmitting and receiving antennas with a circular aperture of diameter D and aperture efficiency η_a at wavelength λ can be found using the relation-

$$G = \eta_a \, (\pi D / \lambda)^2 \qquad \ldots(6.2)$$

The gain calculated using Equation 6.2 is in linear units, not in decibels. The value of antenna efficiency denoted by η_a lies in the range of 0.55 to 0.73 for most parabolic antennas. [25] We use a value 0.65 for the uplink calculations.

Considering the above points, link budgets can be calculated for each channel in each link of the system. The results of link budgets for each channel will vary slightly.

However, the values calculated can be used as a reference to analyze the performance characteristics of the system.

Link	Frequency	FSPL	Bandwidth
Village station to satellite – uplink	14.493 GHz	207.7 dB	36 MHz
Satellite to central hub – downlink	10.954 GHz	205.2 dB	36 MHz
Central hub to satellite – uplink	14.004 GHz	207.4 dB	36 MHz
Satellite to village station – downlink	11.191 GHz	205.4 dB	36 MHz

Table 6.1: Free space path loss (FSPL) on uplinks and downlinks

6.3 Link Budget Considerations

Since a link budget is the accounting of all of the gains and losses from the transmitter, through the medium to the receiver in a telecommunication system, it needs to take into account the attenuation of the transmitted signal due to propagation, as well as the antenna gains, weather and miscellaneous losses. Before calculating the actual link budget for the satellite links used in the proposed project, we enlist some of the terms important in link budget calculations.

System Noise Temperature: Noise temperature provides a way to determine how much thermal noise is generated by active and passive devices in the receiving system. The noise power generated by a device is given by [26]

$$P_n = k\, T_n\, B \qquad \text{...(6.3)}$$

where k is Boltzmann's constant whose value is 1.38 x 10^{-23} J/K; T_n is the noise temperature of the source in Kelvins and B is the bandwidth in hertz.

Transmitter Feeder Loss: The antenna is connected to the other transmitter components by means of waveguides. Losses occur in the connecting waveguides, filters and couplers, reducing the effective power that reaches the antenna.

Antenna Pointing Loss: When a satellite link is established, the ideal situation is to have the satellite and the Earth station antenna beam aligned perfectly for maximum gain. However, this is never the case even for well-designed geostationary satellite communication systems. There are two possible sources of error- one at the satellite end and the other at the village station end. The off-axis loss at of the satellite end antenna beam is taken into account by designing the link to work on within the satellite antenna contour. The off-axis loss at the Earth station is referred to as antenna pointing loss

Transmit EIRP: The equivalent isotropic radiated power (EIRP) is the amount of power that a theoretical isotropic antenna would emit to produce the peak power density observed in the direction of maximum antenna gain and is given by-

$$EIRP\ (in\ dBW) = P_T + G_T - Feeder\ Loss - Antenna\ Pointing\ Loss \qquad \ldots(6.4)$$

Amplifier Back Off: The transmitter uses a traveling wave tube (TWT) amplifier. The input-output characteristic curve of TWT is not linear; the amplifier gain tapers off near saturation. To reduce inter-modulation distortion, the operating point of the TWT must be shifted to the quasi-linear portion of the curve. The resulting reduction in input or output power is referred to as amplifier back-off.

All calculations are made for the worst case of a village station that is located on the – 3dB contour of the Intelsat 906's antenna beam since this covers almost entire landmass of India as seen in Figure 4.1. The central hub station located in Bangalore lies on the –2 dB contour of the satellite beam. Our first task is to calculate the inbound uplink CNR, downlink CNR and overall CNR in the central hub station receiver when the village station has a transmitter output power of 10 watts. The overall CNR calculation is made for a single 8-PSK signal, which is transmitted by transponder #1 at an output power of 50 Watts. Atmospheric loss in clear air for a typical elevation angle does not exceed 0.5 dB at Ku band.

A list of parameters, known and assumed, for initial link budget calculation and their values in linear and decibel units are provided in Table 6.2.

Parameters	Value (Linear units)	Value (Decibel units)
Satellite Transponder Parameters		
Saturated output power (P_t)	100 W	20.0 dBW
Transponder bandwidth (B)	36 MHz	75.6 dBHz
Transponder input noise temperature (T_s)	500 K	27.0 dBK
Transmitter antenna gain, on axis (G)	1995.2	33.0 dB
Village station Parameters		
Transmitter output power – assumed (P_t)	10.0 W	10.0 dBW
Antenna diameter (D)	2.0 m	3.0 dBmtr
Downlink wavelength (λ)	0.026 m	-15.6 dBmtr
Antenna gain, on axis at 14.493 GHz (G_u)	59889	47.7 dB
Antenna gain, on axis at 11.191 GHz (G_d)	35727	45.5 dB
Receiver system noise temperature, in clear air (T_s)	100 K	20.0 dBK
Central Hub Parameters		
Maximum transmit power – assumed ($P_{t\,max}$)	100 W	20.0 dB
Antenna diameter – assumed (D)	5.0 m	7.0 dBmtr
Downlink wavelength (λ)	0.025 m	-16.0 dBm
Antenna gain, on axis at 14.004 GHz (G_U)	349474	55.4 dB
Antenna gain, on axis at 10.954 GHz (G_D)	328959	55.2 dB
Receiver system noise temperature, in clear air (T_s)	200 K	23.0 dBK
Other parameters		
Mean range to satellite – all stations (R)	38,000 km	75.8 dBmtr
Atmospheric losses in clear air	1.59	2.0 dB
Boltzmann's constant (k)	1.38×10^{-23}J/K	-228.6 dBW/K/Hz

Table 6.2: Satellite, central hub and village station parameters for link budget calculations

6.4 Inbound Link Budget in Clear Air

Using data presented in Table 6.1 and Table 6.2 and taking into consideration the constraints presented in Section 6.2, the link budget for the inbound link from a village station to the central hub in Bangalore is calculated.

Inbound Uplink Noise Budget

k	Boltzmann's constant	-228.6	dBW/K/Hz
T	System noise temperature	27.0	dBK
B	Noise bandwidth per 640 kHz channel	58.1	dBHz
N	Noise power at the receiver	-143.5	dBW

Inbound Downlink Noise Budget

k	Boltzmann's constant	-228.6	dBW/K/Hz
T	System noise temperature	20.0	dBK
B	Noise bandwidth for 640 kHz channel	58.1	dBHz
N	Noise power at the receiver	-150.5	dBW

Inbound Uplink Power Budget

P_t	Village hub transmit power	10.0	dBW
G_t	Village hub antenna gain at 14.493 GHz	47.7	dB
G_r	Satellite antenna gain	33.0	dB
L_p	Path loss at 14.493 GHz	-207.7	dB
L_{eob}	Edge of beam loss	-3.0	dB
L_{atmos}	Atmospheric loss	-0.5	dB
L_{misc}	Miscellaneous losses	-1.0	dB
P_r	Received power at the satellite	-121.5	dBW

Inbound Downlink Power Budget

P_t	Transmit power 1 W per channel (initial assumption)	0.0	dBW
G_t	Satellite antenna gain	33.0	dB
G_r	Central hub antenna gain at 10.954 GHz	55.2	dB
L_p	Path loss at 10.954 GHz	-205.2	dB
L_{eob}	Edge of beam loss	-2.0	dB
L_{atmos}	Atmospheric loss	-0.5	dB
L_{misc}	Miscellaneous losses	-1.0	dB
P_r	Received power at the central hub	-120.5	dBW

Inbound Uplink CNR = -121.5 – (-143.5) = 22.0 dB = 158.49

Inbound Downlink CNR = -120.5 – (-150.5) = 30.0 dB = 1000.00

Overall Inbound CNR = 1 / ((1/158.49) + (1/1000.00)) = 136.81 = **21.4 dB**

6.5 Outbound Link Budget in Clear Air

Next step is to calculate the outbound uplink CNR, downlink CNR and overall CNR with a central hub station transmit power of 50 watts. The calculation is made considering a receiver noise bandwidth of 3.2 MHz per channel at the satellite transponder receiver, with the output power of transponder per channel initially set at 1 watt. Using data presented in Table 6.1 and Table 6.2 and taking into consideration the constraints presented in Section 6.2, link budget for an outbound link from the central hub in Bangalore to a village station is calculated.

Outbound Uplink Noise Budget

k	Boltzmann's constant	-228.6	dBW/K/Hz
T	System noise temperature	27.0	dBK
B	Noise bandwidth per 3.2 MHz channel	65.1	dBHz
N	Noise power at the transponder receiver	-136.5	dBW

Outbound Downlink Noise Budget

k	Boltzmann's constant	-228.6	dBW/K/Hz
T	System noise temperature	20.0	dBK
B	Noise bandwidth for 3.2 MHz receiver	65.1	dBHz
N	Noise power at the receiver	-143.5	dBW

Outbound Uplink Power Budget

P_t	Central hub transmit power per channel	0.0	dBW
G_t	Central hub antenna gain at 14.004 GHz	55.4	dB
G_r	Satellite antenna gain	33.0	dB
L_p	Path loss at 14.004 GHz	-207.4	dB
L_{eob}	Edge of beam loss	-2.0	dB
L_{atmos}	Atmospheric loss	-0.5	dB
L_{misc}	Miscellaneous losses	-1.0	dB
P_r	Received power at the satellite	-122.5	dBW

Outbound Downlink Power Budget

P_t	Transmit power 1 W per channel	0.0	dBW
G_t	Satellite antenna gain	33.0	dB
G_r	Village hub antenna gain at 11.191 GHz	55.4	dB
L_p	Path loss at 11.191 GHz	-205.4	dB
L_{eob}	Edge of beam loss	-3.0	dB
L_{atmos}	Atmospheric loss	-0.5	dB
L_{misc}	Miscellaneous losses	-1.0	dB
P_r	Received power at the village hub	-121.5	dBW

Outbound Uplink CNR = -122.5 – (-136.5) = 14.0 dB = 25.11

Outbound Downlink CNR = -121.5 – (-143.5) = 22.0 dB = 158.48

Overall Outbound CNR = 1 / ((1/25.11) + (1/158.48) = 21.67 = **13.4 dB**

These link budgets are valid for clear air conditions. However, the geographical expanse of India covers various climatic zones ranging from tropical rainforests to arid deserts and snow covered mountainous regions receiving varied amounts of rainfall. It is necessary to have an overview of the weather and rainfall patterns in India in order to design links to village stations that can be sustained in rainy weather.

6.6 Weather Patterns in India

The climate of India comprises of a wide range of weather conditions across a large geographic scale and varied topography. According to the Köppen system, India hosts six major climatic subtypes, ranging from desert in the west to alpine tundra and glaciers in the north and humid tropical regions supporting rain forests in the southwest and the island territories. The nation witnesses four major seasons- winter in January and February, summer from March to May, monsoon season from June to September and a post-monsoon period from October to December. The Himalayas act as a barrier to the frigid katabatic winds flowing down from Central Asia. Thus, north India stays warm or only mildly cold during winter while in summer the same phenomenon makes India relatively hot. Although the Tropic of Cancer passes through the middle of India, the whole country is considered to be tropical.

India has a well-defined monsoon period lasting four months. Almost the entire quota of annual rainfall is concentrated around the southwest summer monsoon when massive convective thunderstorms dominate India's weather. The southwest monsoon arrives in two branches- the Bay of Bengal branch and the Arabian Sea branch. The monsoon typically starts around end of May when it lashes the Andaman and Nicobar Islands in the Bay of Bengal. It reaches the Indian mainland in the first week of June near the Malabar Coast of Kerala. By mid June, it reaches Mumbai and appears over Delhi by end of June. The Bay of Bengal branch, which initially tracks the Coromandal Coast northeast from Cape Comorin to Orissa, swerves to the northwest towards the Indo-Gangetic Plain. The Arabian Sea branch moves northeast towards the Himalayas. By the first week of July, the entire country experiences monsoon rain. In an average monsoon, south India receives more rainfall than north India. However, northeast India receives the most precipitation. Monsoon clouds begin retreating from north India by the end of August and it withdraws from Mumbai by first week of October. By the end of November, monsoon leaves the country and negligible amount of rain is received in remaining months of the year. Annual precipitation in different parts of India is shown in Fig. 6.1. [27]

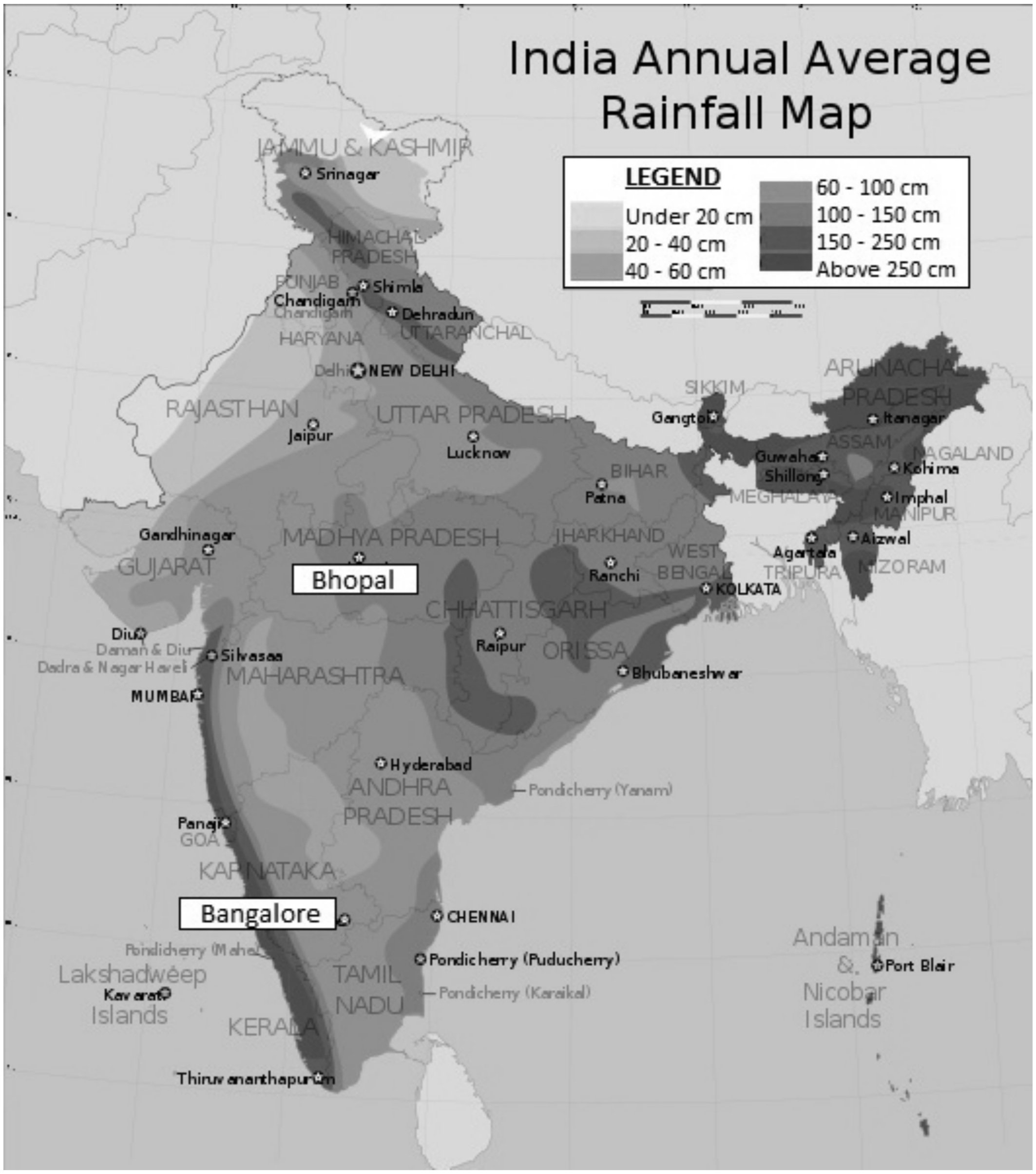


Fig. 6.1: Annual Average Precipitation in various parts of India. Based on data from [33]

For the purpose of this project we will focus our attention on two sample cities for calculating the effect of rain on CNR and link availability. The two cities selected are Bangalore and Bhopal. The rainfall pattern over Bangalore is important because the central network operations hub is proposed to be located in Bangalore. Bhopal is located approximately at the geographical center of India and is hence selected to get typical values of rainfall. The month-wise rainfall distribution in Bangalore and Bhopal is shown in Figs. 6.2 and 6.3 respectively. As seen from Figure 6.1, Bangalore lies in one of the moderate rainfall areas of the country, and this rainfall is relatively evenly distributed over the year instead of heavy concentration in the monsoon season seen in cities along the coast. This is evident from Figure 6.2. Also, Bangalore being a major city with offices of several software companies, there are a number of excellent fiber optic Internet service providers in the city, making it a good choice for location of central hub for the proposed project. On the other hand, as seen in Figure 6.3, the city of Bhopal shows rainfall pattern more typical of the Indian sub-continent, with heavy rains concentrated in the monsoon season and negligible rain in the remaining months of the year.

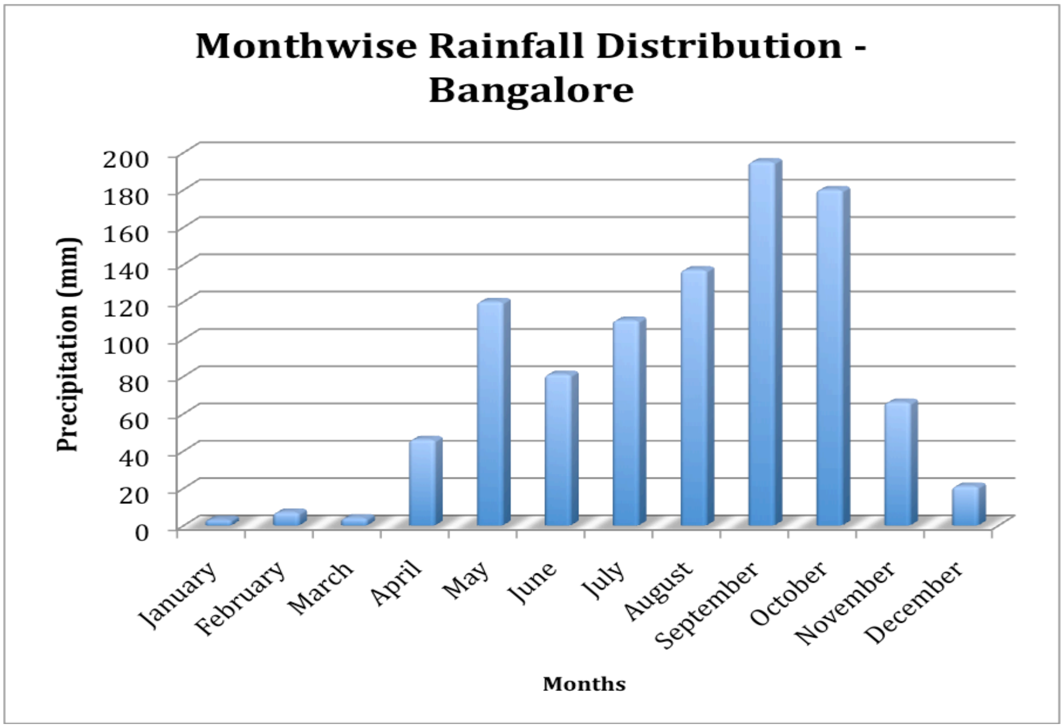


Fig. 6.2: Month-wise rainfall distribution for Bangalore [27]

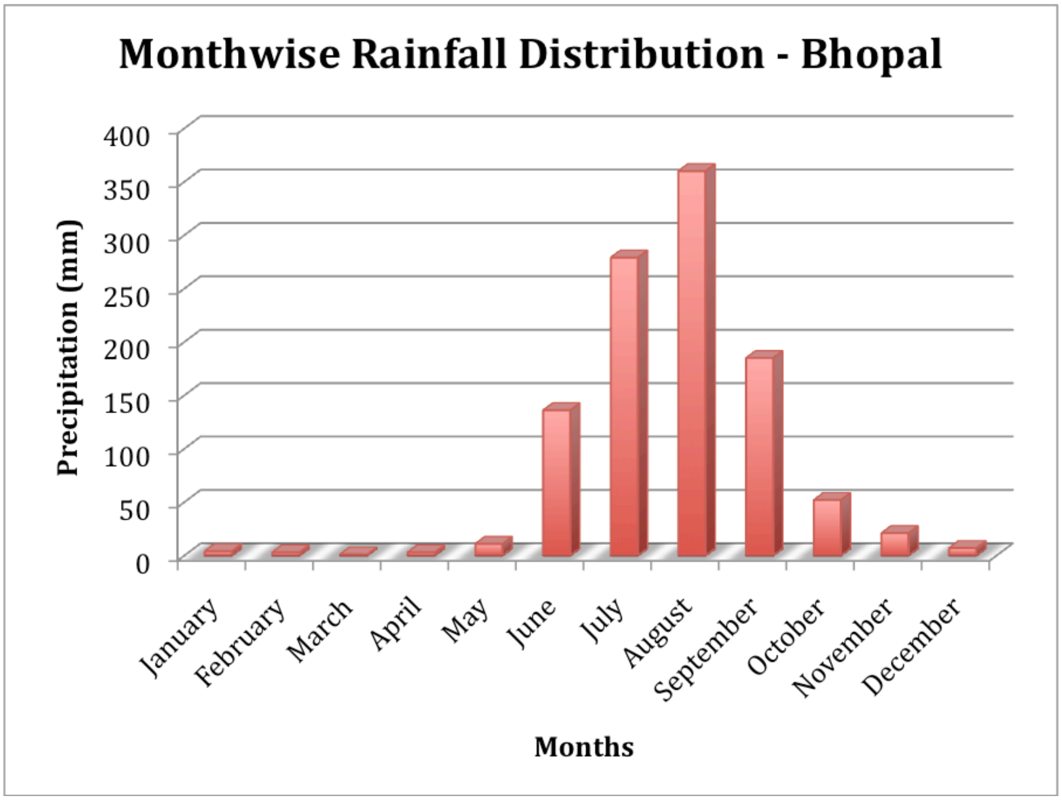


Fig. 6.3: Month-wise rainfall distribution for Bhopal [27]

6.7 Effect of Rain Intensity on Link Budget

At frequencies above 10 GHz, rain is the dominant factor in satellite propagation. The effect of rainfall on a satellite link depends on the intensity of rain at a given time rather than total precipitation. As seen in Figure 6.3 and Figure 6.4, earth station locations in India receive almost the entire annual quota of rainfall during the monsoon months – June to September. During these months, rainfall intensity can exceed 25 mm/hr in a heavy shower, going up to 100 mm/hr during thunderstorms. [28] K_u band links are subject to high attenuation in rain. Since the outbound link from the central hub to the satellite carries data traffic for hundreds of village stations, it is essential to design this link to have as high availability as possible. Considering this, the target outbound link availability is set to 99.9% in dry months, and 99% in the monsoon months for a hub station for which slant path attenuation exceeds 7.0 dB at 11 GHz and 12 dB at 14 GHz, for 0.1 % of an average year. On the other hand, the inbound links can be designed with higher susceptibility to outages since one of those links going down would not affect other village stations. The target availability for inbound link is set at 99.7% availability for a typical village station for which slant path attenuation exceeds 4 dB at 11 GHz and 7 dB at 14 GHz, for 0.3 % of an average year. The link is declared unavailable if the BER exceeds 10^{-6} in the data stream supplied to the customer, or output by the hub station. This is the standard threshold applied to data signals. In case of voice signals, the link could work even if the BER is 10^{-4}. The voice heard over such a link would crack for brief intervals but this is acceptable for voice calls. However the same is not the case with data stream. Hence all links in this project will be considered to be in outage when the BER exceeds 10^{-6}.

There are many models in use to estimate attenuation due to rain. According to one such model developed by Warren Stutzman and Keith Dishman of Virginia Tech [29], if the rain rate R mm/hr is constant over a path of length L km, the attenuation A caused by the rain is given by

$$A = aR^{b}L \text{ (dB)} \qquad \ldots(6.5)$$

The quantity aR^{b} is called the specific attenuation and is measured in decibels/kilometer (dB/km). The coefficients a and b depend upon frequency, polarization, raindrop temperature and other factors. Extensive tabulations on the subject are available, but for the practical purposes of this project, the following approximations given in [29] work well-

$$a = 4.21 \times 10^{-5} f^{2.42} \quad \text{for } 2.9 \text{ GHz} \leq f \leq 54 \text{ GHz} \qquad \ldots(6.6)$$

$$\mathrm{b} = 1.41 f^{-0.0779} \quad \text{for } 8.5 \text{ GHz} \leq f \leq 25 \text{ GHz} \qquad \ldots(6.7)$$

Values of f used in Equations (6.6) and (6.7) are in GHz. The attenuation figures for typical rain rate 25 mm/hr are shown in Table 6.3.

Link	Frequency	Rain Attenuation
Village hub to satellite – uplink	14.493 GHz	1.1 dB/km
Satellite to central hub – downlink	10.954 GHz	0.6 dB/km
Central hub to satellite – uplink	14.004 GHz	1.0 dB/km
Satellite to village hub – downlink	11.191 GHz	0.6 dB/km

Table 6.3: Attenuation in satellite links due to rainfall at 25 mm/hr

Accurate prediction of attenuation due to rain is a complex procedure involving several unknowns. Total path attenuation can be considered as an integral of all the individual increments of rain attenuation caused by the drops encountered along the path. ITU-R has divided the world into 15 rain climatic zones depending on the intensity of rainfall experienced in the area and has published rainfall rate statistics for the 15 rain climate regions. [30] ITU-R has also laid down standard procedures to calculate slant path rain attenuation experienced on satellite links. This procedure will be used in this section to provide estimates of the long-term statistics of the slant path rain attenuation at a given location for a given frequency. The calculations vary depending upon the ITU-R rainfall region in which the earth station is located. For this project, we select two sample locations for calculations – the village of Alibag located along the west coast of India represents a high rain intensity location experiencing thunderstorms in monsoon season while Pokhran located in the arid north-western part of India represents a low rain intensity location. Although it may be satisfactory to achieve 99% availability on the inbound uplinks, calculations for both locations are shown for the criterion of achieving 99.7% availability. The parameters required for rain attenuation calculation are given in Table 6.4.

Parameters	**Alibag**	**Pokhran**
ITU-R rainfall region	N	F
Rainfall rate for 0.01% year in mm/hr ($R_{0.01}$)	100	28
Height above mean sea level in meters (h_s)	0	233
Elevation angle to Intelsat 906 located at 64^o E (θ)	66.15^o	57.52^o
Latitude of earth station (ϕ)	72.88^o	71.92^o
Uplink frequency in GHz (f)	14	14
Effective radius of the earth in km (R_e)	6400	6400
Height of rain selected for calculation (h_R)	4000 m	4000 m

Table 6.4: Required parameters for rain attenuation estimation using ITU-R rainfall data

For $\theta \geq 5^o$, the slant path length L_s under rain is given by

$$L_s = \frac{(h_R - h_s)}{\sin\theta} \qquad ...(6.8)$$

For the village station at Alibag, L_s = 4.373 km. For Pokhran, L_s =4.741 km. The next step is to calculate the horizontal projection of the slant path length, given by

$$L_g = L_s \cos\theta \qquad …(6.9)$$

For the village station at Alibag, L_g = 1.768 km. For Pokhran, L_g =2.546 km. Since the ITU-R regions in which Alibag and Pokhran fall are known, the rainfall rate $R_{0.1}$ exceeded for 0.1% of an average year can be obtained from statistics published by ITU-R. For N zone, $R_{0.1}$ = 35 mm/hr and for F zone, $R_{0.1}$ = 8 mm/hr. The specific attenuation γ_R is given by

$$\gamma_R = k(R_{0.1})^{\alpha} \text{ dB/km} \qquad …(6.10)$$

where k and α are frequency-dependent coefficients given in Recommendation ITU-R P.838. For transmission at 14 GHz considering horizontal polarization, $k = 0.03738$ and $\alpha = 1.1396$. Using these values, for the village station at Alibag, $\gamma_R = 2.149$ dB/km and for Pokhran, $\gamma_R = 0.399$ dB/km. The next step is to calculate the horizontal reduction factor $r_{0.1}$ given by

$$r_{0.1} = \frac{1}{1 + 0.78\sqrt{\frac{L_G \gamma_R}{f}} - 0.38(1 - e^{-2L_G})} \qquad \text{...(6.11)}$$

For Alibag, $r_{0.1} = 0.963$. For Pokhran, $r_{0.1} = 1.201$. The vertical adjustment factor $v_{0.1}$ is calculated as follows

$$\zeta = \tan^{-1}\left(\frac{h_R - h_S}{L_G r_{0.1}}\right) \qquad \text{...(6.12)}$$

For Alibag, $\zeta = 66.943$. For Pokhran, $\zeta = 50.933$. For the Alibag village station, $\zeta > \theta$. So, for this station,

$$L_R = \frac{L_G r_{0.1}}{\cos\theta} = 4.211 \text{ km} \qquad \text{…(6.13)}$$

For Pokhran, $\zeta < \theta$. So, for this station,

$$L_R = \frac{(h_R - h_s)}{\sin\theta} = 4.465 \text{ km} \qquad \text{…(6.14)}$$

For both the stations,

$$v_{0.1} = \frac{1}{1 + \sqrt{\sin\theta}\left(31(1 - e^{-\theta})\frac{\sqrt{L_R \gamma_R}}{f^2} - 0.45\right)} \qquad \text{...(6.15)}$$

For Alibag, $v_{0.1}$ = 0.976. For Pokhran, $v_{0.1}$ = 1.281. The effective path length is given by

$$L_E = L_R \, v_{0.1} \text{ km} \qquad \ldots(6.16)$$

Therefore, for the village station at Alibag, L_E = 4.109 km. For the village station at Pokhran, L_E = 5.719 km. This length is used to calculate the predicted attenuation for 0.1% of an average year, obtained from

$$A_{0.01} = \gamma_R \, L_E \text{ dB} \qquad \ldots(6.17)$$

Hence, for the village station at Alibag located in region of heavy tropical rainfall, the estimated attenuation is 8.831 dB, rounded off to **8.8 dB** for 0.1% of an average year. For the village station at Pokhran in arid region, the estimated attenuation due to rain is 2.281 dB, rounded off to **2.3 dB** for 0.1% of an average year. Similarly, the attenuation for 1% of an average year is also calculated and is found to be 7.0 dB for the Alibag village station in heavy rainfall region and 1.5 dB for Pokhran in dry region.

In our analysis of effect of rain on link performance, we assume that 20 active village stations share the output power of one transponder equally at all times using FDMA-TDM channels. FEC using convolutional coding is used in the inbound and the outbound link and provides a coding gain of 6.0 dB at a BER of 10^{-6} in the recovered data stream. The implementation margin of the 8-PSK demodulators in the central hub receiver is 0.5 dB, and in the village hub receiver the implementation margin is 0.8 dB. We assume that there are always 20 active village stations receiving data from the outbound link in packet form, using TDM and a single 8-PSK carrier. We also assume linear operation of the transponders, but include the effect of increased sky noise when rain is present on the uplink. Transponder #1 (inbound, SCPC-FDMA) is operated with 2 dB output back-off and Transponder #2 (outbound, TDM) is operated with 1 dB back off to ensure operation of power amplifiers in the quasi-linear region.

One way to keep the link up during heavy rain is to use dynamic data sending system. In this system, in case of heavy rain, the network operations center switches off the data link to half the village stations and sends half as much data to the remaining stations at a lower rate by changing modulation from 8-PSK to QPSK depending on the intensity of rain and improvement in CNR desired. This results in better BER on the links that are being serviced. After some time, the central hub changes over the transmission to stations that were not in use earlier and this process repeats. By implementing this scheme the data rate falls by a factor of two, but the links stay up even during heavy rain.

Adaptive FEC can be implemented in many ways. One of the ways to keep the system running during rain is briefly described here. If the uplink is in trouble, there are three options to be considered - service half the total number of stations at full rate for some time and then switch to the other half; send only 2/3 as much data in each packet and keep all stations on line; or send longer packets resulting in twice the delay at every station when QPSK is in use instead of 8-PSK. If the downlink to one station or its uplink is in trouble, we can consider changing the transmitted waveform's modulation type from 8-PSK to QPSK for that station only. The system will still work because the transponders onboard Intelsat 906 are bent-pipe type, merely amplifying and retransmitting any signal received at its input without attempting to demodulate the signal. If the packets are kept of the same duration, the affected station has a data rate that is 2/3 of the date rate in clear air. An alternative to this is to change the FEC code rate to get the desired data rate on the affected link.

6.8 Inbound Link Budget in Rain

We analyze the effect of rain on inbound link performance by determining the intensity of rain that would cause the overall CNR on the link to drop below the threshold required to maintain the link above the specified bit error rate (BER) of 10^{-6}. The analysis is performed for two circumstances - rain in the inbound uplink and rain in the inbound downlink.

Inbound Link Analysis with Rain Attenuation On Uplink

The 99% availability requirement translates to a slant path attenuation that exceeds 4 dB at 10.954 GHz on the downlink to the central hub station and 7 dB at 14.004 GHz on the uplink to the satellite. [13] The minimum permitted BER on any link is 10^{-6}, corresponding to an effective overall $(CNR)_o$ ratio of 18.8 dB for 8-PSK modulation. [31] There is 6.0 dB coding gain from the use forward error correction. [28] Hence the minimum overall $(CNR)_o$ ratio in the hub station receiver is

$$(CNR)_{o\ minimum} = 18.8 - 6.0 + 0.5 = 13.3 \text{ dB} \qquad \ldots(6.18)$$

When rain occurs in the uplink, $(CNR)_{overall}$ in the village station received signal power falls in direct proportion to rain attenuation on the uplink path. The intensity of rain the link can tolerate before $CNR_{overall}$ falls below threshold depends on the amount of attenuation caused by the rain. Consider the rain on uplink adds x dB attenuation. To accommodate x dB uplink rain attenuation we require

$$(CNR)_o = (13.3 + x) \text{ in clear air.} \qquad \ldots(6.19)$$

The value of $(CNR)_{up}$ in the calculation in Section 6.3 in clear air conditions was 22.0 dB with 10 W transmitted by the village station. $(CNR)_{down}$ was 30.0 dB with 1 W per channel transmitted by the satellite. With 20 signals and 2 dB backoff at the transponder output, the transponder transmits 100 W – 2 dB = 18.0 dBW. This power is shared between 20 signals, so P_t per channel is 18.0 – 13.0 = 5.0 dBW. Hence in clear air conditions, $(CNR)_{down}$ = 35.0 dB. With these operating CNR values, $(CNR)_{overall}$ = 21.8 dB in clear air. The amount of attenuation the link can tolerate, x is given by

$13.3 + x = 21.8$, or $x =$ **8.5 dB**

Link budget calculations similar to the ones shown in Section 6.3 yields the following results-

Inbound Uplink CNR = -130.0 – (-143.5) = 13.5 dB = 22.38

Inbound Downlink CNR = -120.5 – (-150.5) = 30.0 dB = 1000.00

Overall Inbound CNR = 1 / ((1/22.38) + (1/1000.00)) = 21.89 = **13.4 dB**

The link budget above verifies that the inbound link will be able to achieve the minimum required overall CNR of 13.4 dB to maintain BER on 8-PSK link under 10^{-6} taking into account 6.0 dB coding gain introduced by FEC when the uplink is affected by rain causing attenuation up to a maximum value of 8.5 dB. This is true if the satellite transponder transmits at its maximum saturated power (100 W). However, as the satellite ages, the performance of its solar panels deteriorates and it may not be possible to obtain full power from transponders of a satellite nearing end of its scheduled life. Consider the maximum power available from transponder is only 50 W. Now with 2 dB backoff at the transponder output, the transponder transmits 50 W – 2 dB = 15.0 dBW. This power is shared between 20 signals, so P_t per channel is 15.0 – 13.0 = 2.0 dBW. Hence in clear air conditions, $(CNR)_{down}$ = 28.0 dB. With these operating CNR values, $(CNR)_{overall}$ = 21.0 dB in clear air and the amount of attenuation the link can tolerate now is given by

$$13.3 + x = 21.0, \text{ or } x = \mathbf{7.7\ dB}.$$

From Equation 6.5, we know attenuation due to rain is given by $A = aR^bL$ (dB). Using this equation, the corresponding rain intensity for a particular value of attenuation can be calculated. If the length of the link under rain (L) is known, the rain rate R causing attenuation A is given by

$$R = \left(\frac{A}{aL}\right)^{\frac{1}{b}} \qquad ...(6.20)$$

where a and b are given by Equation 6.6 and 6.7 respectively. If the rain is concentrated in a smaller portion of the link, it is possible to tolerate relatively heavier rain. Table 6.5 shows the maximum rain intensity that can be tolerated on the inbound uplink when the rain affects varying lengths of the link. It is known that widespread rain cannot exceed 10 mm/hr. Convective rain caused by thunderstorms can exceed this value, and it often happens in coastal parts of India prone to tropical thunderstorms. However, this tends to be in localized downpours thereby affecting only a small length of the link.

Inbound Link Analysis with Rain Attenuation on Downlink

The limiting condition for the downlink is $(\mathrm{CNR})_{\mathrm{overall}} = 21.8$ dB with x dB rain attenuation on the downlink. Analysis of effect of rain on downlink is more complicated than rain on uplink because when it rains on downlink, the sky noise temperature perceived by the receiver will increase due to the rain in the path. The increase in sky noise temperature is given by [32]

$$T_{\mathrm{sky\ rain}} = T_o\,(1 - 10^{-A/10}) \qquad \ldots(6.21)$$

where T_o is the ambient temperature in Kelvins and A is the attenuation due to rain in decibels.

For example, for a medium temperature of 290 K and rain attenuation 4.0 dB observed in parts of India receiving moderate rainfall, falling in ITU-R climate zone M and N,

$$\mathrm{T}_{\mathrm{sky\ rain}} = 290\,(1 - 10^{-4.0/10.0}) = 174.5\ \mathrm{K}$$

The clear sky noise temperature is

$$\mathrm{T}_{\mathrm{sky\ clear\ air}} = 290\,(1 - 0.631) = 107\ \mathrm{K}$$

The receiver LNA contribution is 200 – 107 = 93 K, giving $\mathrm{T}_{\mathrm{s\ rain}}$ = 174.5 + 93 = 267.5 K. The increase in system noise power is therefore

$$\Delta\mathrm{N} = 10 \log (267.5 / 200) = 1.3\ \mathrm{dB}$$

giving a total reduction in $(\mathrm{CNR})_{\mathrm{dn}}$ of 4.0 + 1.3 = 5.3 dB. This means, a 4.0 dB attenuation due to rain on downlink effectively results in a 5.3 dB reduction in CNR, taking into consideration the effect of increased sky temperature. The effective attenuations due to different values of rain attenuation are shown in Table 6.5.

Rain Attenuation (dB)	**T_{sky} (K)**	**$T_{sky\ rain}$ (K)**	**ΔN (dB)**	**Total CNR reduction (dB)**
2.0	107.0	200.0	0.0	2.0
3.0	144.7	237.7	0.7	3.7
4.0	174.5	267.5	1.3	5.3
5.0	198.3	291.3	1.6	6.6
6.0	217.2	310.2	1.9	7.9
7.0	232.1	325.1	2.1	9.1
8.0	244.0	337.0	2.3	10.3
9.0	253.5	346.5	2.4	11.4
10.0	261.0	354.0	2.5	12.5
11.0	267.0	360.0	2.6	13.6
12.0	271.7	364.7	2.6	14.6
13.0	275.5	368.5	2.7	15.7
14.0	278.5	371.5	2.7	16.7
15.0	280.8	373.8	2.7	17.7

Table 6.5: Total reduction in CNR due to increase in sky noise temperature caused by rain of varying intensity on downlink.

Based on a receiver noise bandwidth of 640 kHz, the clear air downlink CNR ratio was $(CNR)_{dn\ ca}$ = 30.0 dB, so in this bandwidth $(CNR)_{dn\ rain}$ = (30.0 - y) dB. In clear air conditions the overall $(CNR)_{overall}$ ratio in the hub receiver for a transmission from a village station with y dB rain attenuation on the downlink is

$$(CNR)_{overall\ rain} = 1 / [\ 1 / 10^{22.0/10} + 1 / 10^{(30.0-y)/10}\ ] \qquad \ldots(6.22)$$

If this link is to maintained, this value should be greater or equal to the minimum permitted value of 14.3 dB, which requires

$$1 / 10^{14.3/10} = 1 / [\ 1 / 10^{22.0/10} + 1 / 10^{(30.0-y)/10}\ ] \qquad \ldots(6.23)$$

which, on solving, yields y = **14.9 dB.** This is the maximum permitted attenuation due to rain on the downlink if the link is to be maintained above the specified BER of 10^{-6}. As seen from Table 6.5, effective reduction in CNR of 14.9 dB corresponds to rain attenuation of approximately 12.0 dB. This value is to be used when calculating the corresponding rain intensity. If the maximum rain attenuation allowed is 12.0 dB and it is known what length of the link from the satellite to central hub is affected by rain, the maximum theoretical rain intensity that can be tolerated by the link before its BER goes below 10^{-6} can be calculated from Equation 6.20.

Link budget calculations similar to the ones shown in Section 6.3 yield the following results-

Inbound Uplink CNR	= -121.5 – (-143.5)	= 22.0 dB	= 158.49	
Inbound Downlink CNR	= -132.5 – (-150.5)	= 18.0 dB	= 63.09	
Overall Inbound CNR	= 1 / ((1/158.49) + (1/63.09))		= 45.12	= **16.5 dB**

The link budget above verifies that the inbound link will be able to achieve overall CNR greater than the minimum required overall CNR of 13.4 dB when the downlink is affected by rain causing attenuation up to a maximum value of 12.0 dB.

6.9 Outbound Link Budget in Rain

In this section we determine the maximum rain attenuation the outbound link can tolerate to meet the availability criterion under two circumstances - rain in the outbound uplink and rain in the outbound downlink.

Outbound Link Analysis with Rain Attenuation on Uplink

The minimum permitted BER on any link is 10^{-6}, corresponding to an effective overall $(CNR)_o$ ratio of 18.8 dB for 8-PSK modulation. The implementation margin of the village hub receiver is 0.8 dB. There is 6.0 dB coding gain from the use of forward error correction. Hence the minimum $(\mathrm{CNR})_{\mathrm{overall}}$ ratio in the village station receiver is

$$(\mathrm{CNR})_{\mathrm{o\ minimum}} = 18.8 - 6.0 + 0.8 = 13.6 \text{ dB} \qquad \ldots(6.24)$$

When rain occurs in the uplink, $(\mathrm{CNR})_{\mathrm{overall}}$ in the village station receiver falls in direct proportion to rain attenuation on the uplink path. For x dB attenuation caused by rain on uplink, we require

$$(\mathrm{CNR})_{\mathrm{overall}} = (13.6 + x) \text{ dB in clear air.} \qquad \ldots(6.25)$$

The value of $(\mathrm{CNR})_{\mathrm{up}}$ in the clear air calculation in Section 6.4 was 14.0 dB with 1 W per channel transmitted by the central hub in a channel noise bandwidth of 3.2 MHz. $(\mathrm{CNR})_{\mathrm{down}}$ was 22.0 dB with 1 watt per channel transmitted by the satellite.

The 20 signals destined for the VSAT stations are transmitted as a TDM bit stream at 3.2 Msps. We should increase the hub station transmit power to 20W now that there are 20 signals to be sent by TDM, giving $(\mathrm{CNR})_{\mathrm{up}} = 27.0$ dB in clear air in 3.2 MHz receiver noise bandwidth. The transponder has 1 dB backoff at the transponder output, and its maximum saturated power of 100 watts is equally divided among 10 channels. So for each channel, it transmits 10 W – 1 dB = 9.0 dBW. Hence, in clear air conditions, $(\mathrm{CNR})_{\mathrm{down}} = 22.0 + 9.0 = 31.0$ dB. With these values, $(\mathrm{CNR})_{\mathrm{overall}} = 25.5$ dB in clear air. Hence, the rain attenuation the link can tolerate to minimum permitted overall CNR ratio is given by $(13.6 + x) = 25.5$, giving $x =$ **11.9 dB.** If the maximum allowed attenuation is 11.9 dB and it is known what length of the link is affected by rain, the maximum theoretical rain intensity that the link can tolerate can be calculated from Equation 6.20.

Outbound Link Analysis with Rain Attenuation on Downlink

Similar to the analysis for the inbound link, analysis of the effect of rain on an outbound downlink needs to take into consideration because the sky noise temperature perceived by the receiver will increase due to the rain in the path. Equation 6.18 gives the increase in sky noise temperature. Due to rain and resultant increase in noise temperature, assume $(CNR)_{down}$ falls by y dB from its clear air value of 31.0 dB to a new value of $(31.0 - y)$ dB. $(CNR)_{uplink}$ in clear air is 27.0 dB which is not affected by rain on downlink. In clear air conditions the overall $(CNR)_{overall}$ ratio in the village station receiver for a transmission from the central hub station with y dB rain attenuation on the downlink is

$$(CNR)_{overall\ rain} = 1 / [\ 1 / 10^{27.0/10} + 1 / 10^{(31.0-y)/10}\ ] \qquad \ldots(6.26)$$

If this link is to maintained, this value should be greater or equal to the minimum permitted value of 13.6 dB, which requires

$$1 / 10^{13.6/10} = 1 / [\ 1 / 10^{27.0/10} + 1 / 10^{(31.0-y)/10}\ ] \qquad \ldots(6.27)$$

which, on solving, yields y = **17.2 dB**. This is the maximum permitted reduction in CNR due to rain on the downlink if the link is to be maintained above the specified bit error rate of 10^{-6}. As seen from Table 6.5, effective reduction in CNR of 17.2 dB corresponds to rain attenuation of approximately 14.5 dB. This is the value to be used while calculating maximum tolerable rain intensity. If the maximum allowed attenuation due to rain is 14.5 dB, the maximum tolerable rain rate to maintain link can be calculated using Equation 6.20.

6.10 Link Availability in Rain

In the previous sections, we calculated the maximum margin available on inbound and outbound links to tolerate attenuation due to rain. Using Equation 6.20, it is possible to determine the maximum theoretical rain intensities that can be tolerated on each of the four links depending upon the length of the link affected by rain. These values are given in Table 6.6.

Length of link affected by rain (km)	**Max theoretical rain intensity tolerated on the link (mm/hr)**			
	Inbound Uplink	**Inbound Downlink**	**Outbound Uplink**	**Outbound Downlink**
1.0	160.4	322.7	215.0	379.4
2 .0	87.7	178.4	117.5	209.7
3 .0	61.6	126.2	82.6	148.3
4 .0	48.0	98.6	64.2	116.0
5 .0	39.5	81.5	52.9	95.8
6 .0	33.7	69.7	45.1	82.0
7 .0	29.5	61.1	39.5	71.8
8 .0	26.2	54.5	35.1	64.1
9 .0	23.6	49.3	31.7	58.0
10 .0	21.5	45.0	28.9	53.0

Table 6.6: Maximum tolerable rain intensity on inbound uplink when different lengths of the link are affected by rain

It is seen from the table that the maximum rain intensity that each link can tolerate decreases as the length of the link affected by rain increases. Each of the links can tolerate very high intensity of rain if it occurs on only a small portion of the link while being able to tolerate a much lower intensity of rain if it is spread over a longer part of the link. The values mentioned in Table 6.5 are theoretical maximum intensities that can be tolerated on each link. However, in practice rainfall with such high intensities is never observed. Under normal circumstances, rain scattered over several kilometers is never more intense than 20 mm/hr. However, convective rain due to thunderstorms occurring over a very small area can be more intense, measuring up to 50 mm/hr. The coastal regions of India along the Arabian Sea as well as Bay of Bengal receive such thunderstorms several times during the monsoon season. So, links to village stations located in the coastal areas should be able to withstand rain intensity of this magnitude occurring on a small length, generally 1 km to 2 km. The maximum theoretical rain intensity each link can tolerate and its comparison with the actual rain intensities experienced under normal conditions and thunderstorms is shown in Figure 6.4. It is clear from the graph that all the links have enough margins to tolerate normal rain occurring up to a length of more than 10 km on the link and heavy convection rain as long as it is concentrated in an area covering less than 3 km of the link, which is usually the case in practical environment.

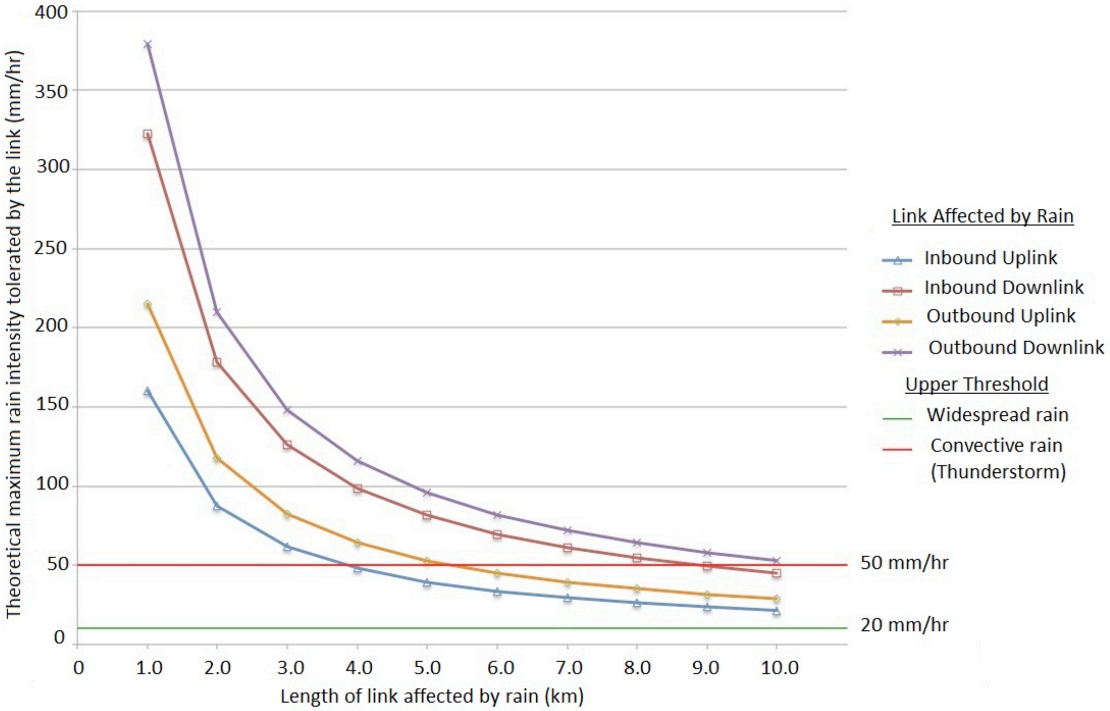


Fig. 6.4: Comparison of maximum theoretical rain intensity tolerated by each link with practically experienced rain intensities.

6.11 System Optimization

The system design proposed in Chapter 6 is capable of serving 4800 village stations simultaneously using 24 Ku band transponders onboard Intelsat 906 in clear weather as well as in heavy rain. While it is desirable to have a communication link available in all weather conditions, the disadvantage of the design proposed in Chapter 6 in context of development of a basic communication system for remote areas is that the system is capable of effectively serving only 1% of the total number of villages in India. In order to provide Internet access to a wider population, it is necessary to make the availability criteria less stringent, allowing the system to operate at lower CNR margins enabling higher overall throughput of data.

The target in this section is to optimize and increase the capacity of the system so that one satellite is able to serve close to 10% of the total number of villages. Once this is achieved, time-based staggering can be used to allocate a few hours per day to each village instead of a 24-hour dedicated link, and thereby increase capacity to reach close to the goal of serving all the villages of India. Admittedly, some communication capacity is better than none, and the greater the number of villages served by the system using a single satellite, the more economically attractive the project becomes to the investors and funding sources.

One way to increase capacity is to run the system with a very low rain margin. When heavy rain affects a particular village or region, the Internet link from affected villages is taken off and handed over to a different region of the country where the rain at the same time is not as heavy. Every 3 dB of excess margin halves the number of users that can be served. As seen in Section 6.3, the inbound link budget in clear air for the original design has a large margin, especially if use of QPSK is considered. With good FEC using convolution codes decoded using Viterbi algorithm, the CNR threshold to maintain the BER is around 6 dB, so the margin in the system is 21.4 – 6.0 = 15.4 dB. If it is decided to operate the system in clear air with a margin of 2.4 dB, it results in a 13 dB gain in CNR, which translates to 20 times increase in bit rate, in theory. This means it is possible to serve 20 times as many villages using the same link.

If this improvement is applied on all the links, the theoretical capacity of the system increases from 4,800 villages to 96,000 villages. However, this is not the only criterion that determines the overall capacity of the system. As seen in Section 6.4, the outbound link budget in clear air has a margin of 7.4 dB above the threshold, which is smaller than the margin on the inbound link. Once again, considering the system is operated with a 2.4 dB margin in clear air, it results in a 5.0 dB gain in CNR, thereby allowing three times the bit rate, theoretically. The increase in available bit rate is accompanied by a reduction in sustainability of the link in rain. Equation 6.5 gives the relationship between attenuation due to rain and maximum rain intensity tolerated by the link. The greater the CNR margin added on the link to overcome attenuation due to rain, lower is the bit rate and, effectively, the number of village stations that can be served. A comparison of the tradeoff between number of village stations that can be served and the maximum rain intensity that the inbound uplink and downlink can tolerate when rain is present on 5 km of the link, for different values of CNR margin at which the link can be operated provided in Table 6.7.

CNR Margin on link (dB)	**Max No. of village stations**	**Max Rain Intensity on Uplink (14 GHz) (mm/hr)**	**Max Rain Intensity on Downlink (11 GHz) (mm/hr)**
2.4	96000	13.11	20.59
5.4	48000	26.58	41.19
8.4	24000	39.06	60.1
11.4	12000	50.97	78.03

Table 6.7: Comparison of number of village stations served by the inbound link when the link is operated with varying rain tolerance

As seen from the table, the originally designed link is capable of serving up to 96,000 villages in clear air, or light rain; however, if the Internet link is to be sustained in heavy thunderstorms, the data rate has to be reduced and effectively only 12,000 villages can be served. However this is only an approximate figure because rain does not affect the entire region of India simultaneously and in uniform proportion. Heavy thunderstorms resulting in rain intensity above 50 mm/hr occur only in coastal plains and the northeastern region of India during the monsoon season. Also, most of the times, heavy thunderstorms are localized over a small geographical area, thereby affecting only a few villages at a time. When this happens, the links to affected villages can be operated with higher CNR margin, while links to villages not affected by rain can operate on lower CNR margin. These changes need to be implemented from the central hub depending on outage statistics for the particular localities.

Chapter 7

Project Feasibility

This chapter provides an overview of the technical and commercial feasibility of the proposed system in terms of availability, extent of reach in rural India, cost analysis and social impact of the system.

7.1 Data Rates and System Availability

Two possible designs for the low-cost Internet system for rural India have been proposed in the previous chapters. The original design has sufficient CNR margins and is capable of providing a 4.8 Mbps outbound data link to a village station under clear air and heavy rain conditions using Gray coded 8-PSK modulation and FEC with a fixed convolution code. However, this system is inefficient in terms of the number of villages, and subsequently, number of customers served since it is possible to provide uninterrupted Internet access to only 4,800 villages using all the Ku band transponders onboard Intelsat 906.

The optimized system design explained in Chapter 6 is capable of serving a wider customer base. The proposed system uses adaptive modulation, shifting between 8-PSK, QPSK and BPSK depending on weather conditions, and also making use of adaptive FEC. As mentioned in Section 6.10, the number of village stations being served, the modulation technique being used, and resultant data rate available to each village station are dynamically varying and depend on the prevailing weather condition. A maximum of 96,000 village stations can be constructed to be served by the infrastructure available by using one central hub and all the Ku band transponders onboard Intelsat 906. However, in this case, the system cannot offer a guaranteed quality of service and is said to be operating on best effort delivery model. Best effort delivery describes a network service in which the network does not provide any guarantee that the data is delivered or that a user will get a guaranteed quality of service level or a certain priority. In a best effort network all users obtain best effort service, meaning that they obtain unspecified variable bit rate and delivery time, depending on the prevailing conditions on the network.

7.2 Cost Analysis of Components

The success of the proposed system depends predominantly on the final cost per customer at which it is possible to deliver Internet access. Before a potential pricing model can be developed, it is necessary to evaluate the approximate total cost of installation, deployment and maintenance of the system. The total cost of the system includes cost of leasing the satellite from Intelsat at a negotiated low price considering its age, setting up the central hub, and setting up village stations all over the country. The total cost will depend upon the number of village stations set up, depending upon the initial demand and the overall response from rural India, which can only be speculated.

The central hub is proposed to be set up near an urban area in Bangalore in south India, the reasons for which have been explained in Chapter 6. Also, a nationwide commercial Internet service system requires redundancy to allow for occasional failure and downtime for maintenance of the primary hub. A second central hub can be setup in Noida, near New Delhi in north India. As seen in Figure 6.1, this location falls in moderate rainfall region and is therefore a better location for central hub compared to other major cities of India such as Mumbai, Kolkata and Chennai, all of which are located along the coast in heavy rainfall zones. The cost for central hub also includes the cost of land acquisition and construction costs. The most expensive component of the central hub is the 5 m diameter antenna costing approximately $100,000. In addition, the central hub requires components such as high power amplifiers, splitters, mixers, oscillators, adaptive PSK modulators and power supply to fulfill the energy requirements of all the components. Also, a diesel generator is required to provide backup power in case of electricity supply failure. Since it is proposed that the optimized system will have adaptive modulation, adaptive FEC and dynamically changing data rates and links directed to different village stations at different times, considerable computational hardware and skilled staff to operate, maintain and troubleshoot the system are required at the central hub. The approximate costs of the major components used in the central hub as per April 2011 market estimates are provided in Table 7.1. All prices mentioned are indicative, mentioned only for academic interest and the author assumes no responsibility for discrepancies, if any, from actual prices in the market.

Unlike the central hub, the village station is proposed to be an unmanned self-sufficient self-powering module since it will be installed in remote locations in rural areas. The village station module is designed to act as the earth station for satellite link as well as Wi-Fi hotspot. All the equipment required for these purposes will be enclosed in a weather protected metal rack enclosure capable of withstanding temperature variation from 0^{o} C to 50^{o} C and protecting the equipment from heavy rain. Apart from equipment required for demodulation of Ku-band signals and Wi-Fi transmission, the village station enclosure also houses batteries for power supply connected to a pedal power generator for power backup. Association for India's Development (AID) in collaboration with the Industrial Design Centre, IIT-Mumbai has designed bicycle pedal powered generators capable of generating 40 Watts of electricity per hour of pedaling. [33] This unit costs INR 7500 (approximately US $ 250) without any subsidy. Manufacturing in large volumes can further reduce the cost of these units. It is proposed that a suitably modified version of this unit be installed in every village station. The costs of various components of the central hub are shown in Table 7.1. Similar cost analysis for village station is provided in Table 7.2.

Component	Cost per unit
Land for hub building – 100 m^2 in Bangalore @ \$100/m^2	\$10,000
5 m diameter antenna	\$100,000
Hub equipment racks including LNA, HPA, splitters etc	\$100,000
6 kW diesel generator	\$1,000
Satellite modem and computer systems	\$50,000
Cables, waveguides and miscellaneous costs	\$4,000
Total cost	**\$265,000**

Table 7.1: Approximate costs for central hub components

Component	Cost per unit
Outdoor - Ku band outdoor dish, feed, transmit reject filter	\$ 900 [34]
Indoor – Adaptive PSK modulator, LNA, HPA	\$ 900 [34]
Wi-Fi router + range extending antenna	\$ 200
600W 12V Car Batteries	\$500
Tracking antenna controller	\$1500
Pedal powered generator developed by AID	\$ 250 [33]
200 W 12 V solar panel	\$ 500
Metal housing case, cables and miscellaneous costs	\$ 250
Total Cost	**\$5,000**

Table 7.2: Approximate market cost of village station components

7.3 Commercial Deployment and Pricing Model

Since the proposed low-cost satellite Internet system uses Intelsat 906, a geostationary satellite that could be put to other use, even in slightly inclined orbit, it is necessary to provide an economic justification for commercial implementation of the system proposed in this thesis. The proposed system is scalable and can be deployed in phases depending on customer demand and available capital for investment. Although a detailed discussion of market economics, advertising and revenue model is beyond the scope of this thesis, in this section we propose possible two approaches of deployment and their corresponding pros and cons.

The first pricing model we propose is to implement the system in the first phase only in 4,800 villages in a specific part of India. As explained in Chapter 6, this is the number of villages that can be provided an almost uninterrupted Internet access in clear air and heavy rain. The cost of setting up one central hub, one redundant hub and 4,800 village stations, calculated using data in Table 7.1 and Table 7.2 comes to $ 24,530,000. After adding the cost of leasing the satellite, initial Internet access setup cost with ISP and cost of human labor, the system can be estimated to be setup with an initial investment of approximately $ 28,000,000. Also, consider the Ku band transponders on the ageing Intelsat 906 are leased at a bargained cost that is 10% of the original leasing cost of transponders on a new satellite. This translates to operating costs around $4,000,000 per annum.

As explained in Chapter 1, in the period between June 2008 and June 2010, owing to substantial reduction in call costs per minute, the cellular telephone market in rural India experienced an annual growth of 43%, growing from 286 million customers in June 2008 to 601 million customers in June 2010. [3] Considering this market trend, it can be expected that a similar low-cost Internet service will also experience customer growth along similar lines. Starting with an assumption that on an average, 100 customers sign up for the low-cost Internet service in every village where the system is implemented in the first stage, and keeping the access cost-per-month per-customer limited to $ 1 as was the initial target at the outset, the revenue earned by the system will be $576,000 in the first year. Since the exact reception among the rural population of India is not known at present, we can speculate two scenarios- either the system is received well among the rural population and the number of customers grows at a compounded rate of 20% per annum, or the system receives lukewarm response from the rural population and the customer base grows by only 10% annually. The total expenditure on the system, including initial capital investment and recurring operating costs, and the total revenue accumulated over a period of time in both scenarios is shown in Figure 7.1.

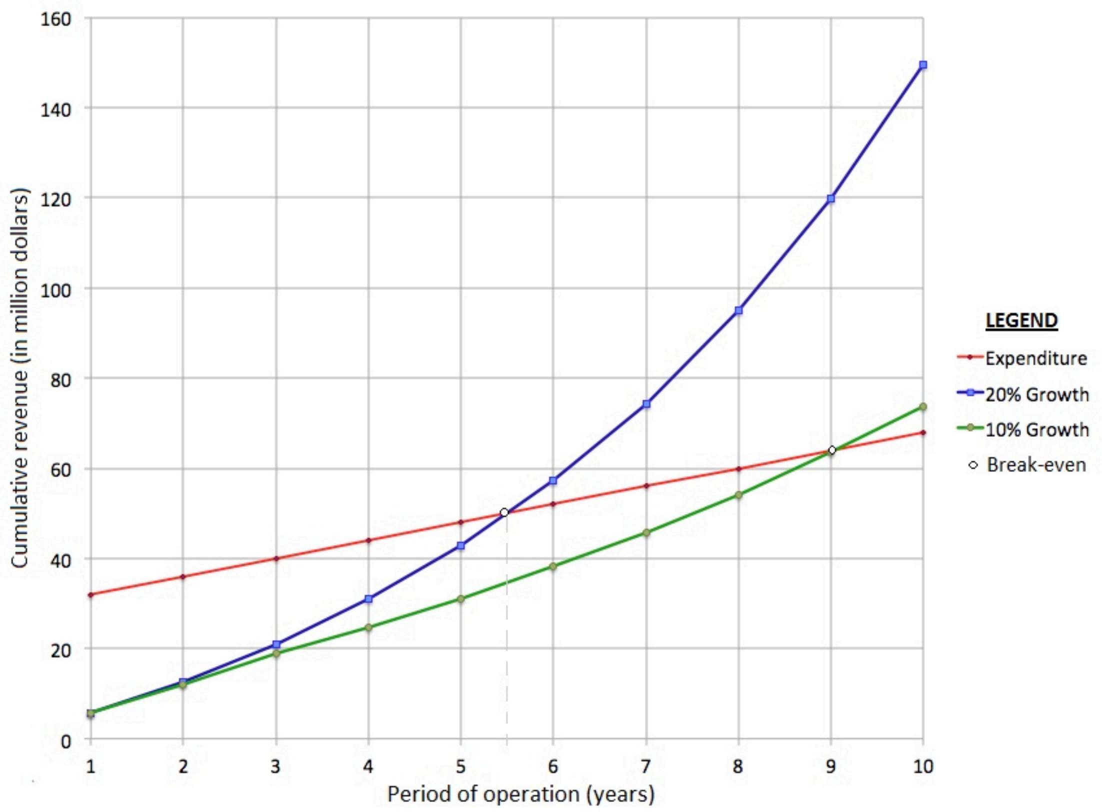


Figure 7.1: Total expenditure and revenue earned by implementing system in 4,800 villages with 100 customers per village at an access cost of $1 per customer

As seen from the figure, if the customer base grows at 20% per annum, the system will be able to break-even during the fifth year of operation and starts yielding profits thereafter. If the customer growth is limited to 10% per annum, the system reaches the break-even point after nine years of operation. However, this system reaches its capacity limit at 4,800 villages and addition of any more villages will result in degradation of service for all customers. It is not a good business idea to give customers a high quality service initially and lower the quality later. A better business proposal is to begin with widespread coverage with best-effort quality of service and adding infrastructure over time to improve data rates and availability with time. This can be achieved by using the optimized system design explained in Section 6.10.

Since the main objective of the proposed system is to provide Internet access to remote rural areas deprived of conventional means of Internet access, the reach of the system to maximum population is more important than data rates or sustained availability at any particular village station, and hence we need to consider the economic implications of deploying the optimized system capable of serving 96,000 villages in clear air, with no guarantee of service during rainy weather. The cost of setting up one central hub, one redundant hub and 96,000 village stations, calculated using data in Table 7.1 and Table 7.2 comes to \$ 480,530,000. After adding the cost of leasing the satellite, initial Internet access setup cost with ISP and cost of human labor, the system can be estimated to be setup with an initial investment of approximately \$ 500,000,000. Also, considering the fact that the optimized system requires more computing power and operating staff at the central hub to implement dynamically changing links with adaptive modulation and adaptive FEC, and having 20 times more number of village stations, we can assume the operating costs in this case would be around \$15,000,000 per annum.

Once again, starting with an assumption that on an average, 100 customers sign up for the low-cost Internet service in every village where the system is implemented in the first stage, keeping the access cost-per-month per-customer limited to \$1 as was the initial target at the outset, and also providing customers an incentive to purchase the subscription in spite of no guarantee of service during monsoon months by billing them only for ten months for twelve months of Internet access, the revenue earned in the first year will be \$96,000,000. As explained in the previous case, we consider two scenarios that the customer base grows either by 20% per annum or by 10% per annum. The expenditure and revenue earned over a period of time is shown in Figure 7.2. As seen from the figure, if the customer base grows at 20% per annum, the system will be able to break-even after three years of operation and starts yielding profits thereafter. Even if the customer growth is limited to 10% per annum, the system reaches the break-even point before the end of four years of operation.

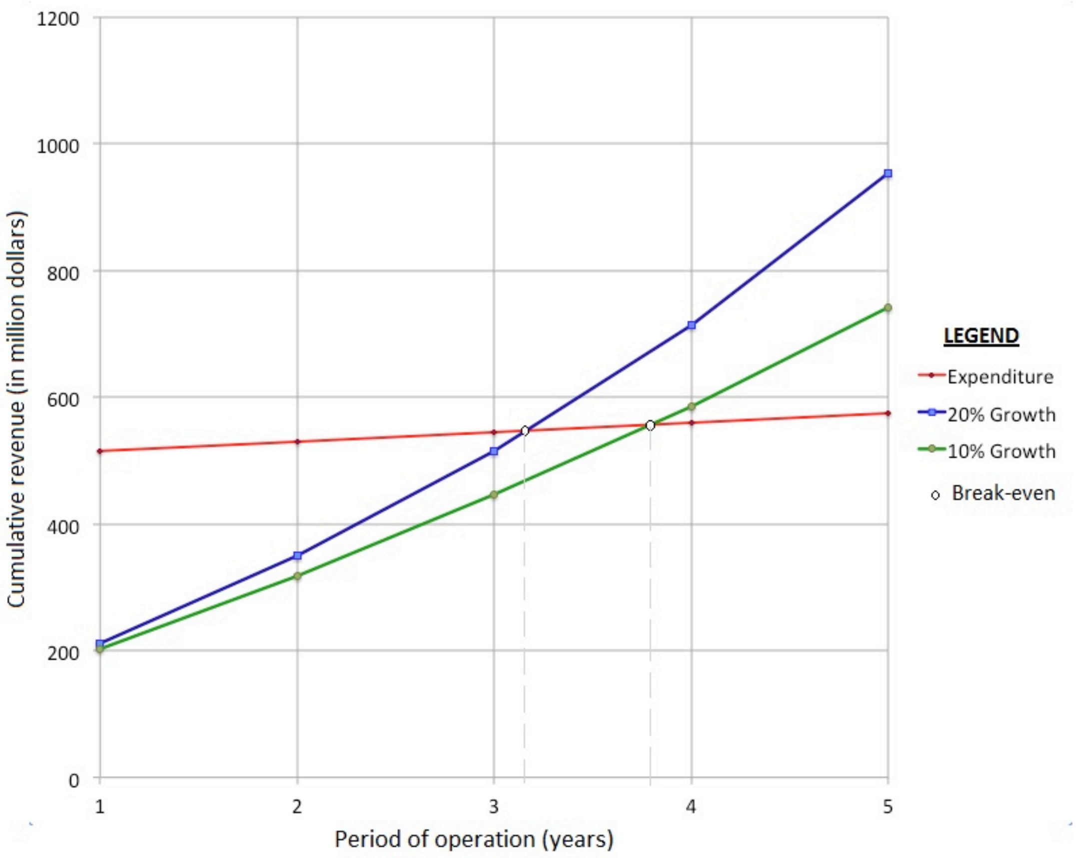


Figure 7.2: Total expenditure and revenue earned by implementing system in 96,000 villages with 100 customers per village at an access cost of $1 per customer

7.4 Availability and Outages

As explained in Section 6.10, the optimized system proposed here is designed to provide Internet access on a best-effort basis, without quoting a fixed guaranteed upload or download speed. The browsing speed available to the customers will depend on two factors- the prevailing weather condition at a particular village, since the modulation and FEC being used on the link is varied dynamically depending upon the CNR link margin available on the link, and the number of users simultaneously accessing the Internet from a given village at a given time.

Apart from disruptions due to weather, the proposed system also needs to take into account the disruptions caused by interference with other geostationary satellites operating at Ku band in the vicinity of Intelsat 906. Since the satellite being used for the proposed system is orbiting in a slightly inclined geosynchronous orbit, its distance from adjacent satellites in GEO orbit slots varies continuously. If at any point, the interference caused by uplink to our selected satellite exceeds the threshold acceptable to adjacent satellites, it might become necessary to switch off all the uplinks when the satellite crosses the GEO orbit to avoid interference with adjacent satellites, as explained in Section 4.7. The level of interference needs to be monitored from the central hub where software can be programmed to automatically shutdown transmission when the interference crosses a pre-decided threshold and restart the transmission when the level of interference is back within acceptable limits.

This type of discontinuity in Internet service might not find favor among commercial and urban customers, however it is unlikely to be a deterrent to users in the rural areas who do not have access to alternate means of accessing the Internet. As mentioned in Section 7.3, the recommended cost of access for this service per customer is $ 1 per month, which according to currency exchange rates prevalent in April 2011, translates to approximately Indian rupees (Rs.) 45. Taking into account the fact that the cheapest pre-paid cellular phone plan offered by BSNL in rural areas costs the customer Rs. 99 per month [5], and more than 300 million rural customers have opted for this service in the last two years in spite of occasional network congestion issues faced on BSNL network shows that there is a considerably large market in rural India for the successful commercial implementation of the proposed Internet service.

Chapter 8
Conclusions and Future Work

This research was undertaken to propose an affordable satellite-based Internet system for remote areas, which can be implemented in developing countries to provide basic connectivity and aid in economic and social progress. The research has been conducted considering rural India as a case study; however the system design is generic and can be replicated in any country that has sufficient demand.

8.1 Conclusion

A low-cost alternative to existing satellite Internet system, for use in remote rural areas in developing countries has been proposed using rural India as an example for deployment. The motivation for this project was the need to provide Internet access to rural population for economic and social progress, and the shortcomings of existing technology to provide such a service due to cost constraints.

A system using a central hub relaying Internet data to village stations using a Ku band geostationary satellite link is proposed, with each village station further relaying the data wirelessly to customers using Wi-Fi links. The initial high cost of launch and maintenance of a geostationary satellite was proposed to be eliminated by using an existing communication satellite nearing the end of its active commercial life. Intelsat 906 was selected as the satellite for analysis. It was proposed that the satellite, once adapted for the proposed project, would be subjected to only east-west station keeping to save fuel, since north-south station keeping requires ten times more fuel than east-west station keeping. This would cause the satellite to drift into an inclined geosynchronous orbit and appear to be moving in a figure of eight pattern when seen from an earth station. The shape and extent of this pattern for different inclination angle of the orbit was calculated. The results of this analysis showed that the antenna at village stations can track the satellite in one plane only. The concept of using a receiving station located centrally in the village, providing last mile connectivity using Wi-Fi was proposed to eliminate the high cost of individual receiving equipment for customers.

An overview of the system blocks and components required at the central hub and village station was provided without mentioning specific equipment details to serve as a generic guide to constructing the proposed system using locally available material. Various modulation schemes and forward error correcting techniques were compared to get optimum system performance and it was decided that adaptive PSK and forward error correction using convolutional codes would be the preferred choice for the proposed system. Alternately, it is suggested that turbo codes can be used to get a low CNR threshold. A quantitative analysis of the proposed system was conducted by calculating link budgets in clear air and rain, considering the EIRP limitation of village station antenna and satellite transponders, power requirements, available bandwidth and various sources of attenuation. The ITU rain model was used to analyze the effect of rain on system performance.

The tradeoffs in the system design were analyzed. It was concluded that using a single central hub and all Ku band transponders onboard Intelsat 906, the system could either be designed to provide guaranteed Internet access in all weather conditions but limited to only 4,800 villages or to extend the reach of the system to 96,000 villages but provide Internet access on best-effort basis with dynamically varying data rates depending on prevailing weather conditions. Considering the basic purpose of the proposed system, it was decided that the latter approach should be preferred. Preliminary cost analysis of the system was conducted and a possible pricing plan for commercial deployment was proposed, which showed that by keeping the access cost per customer as low as $ 1 per month, it is possible to recover the investment costs in less than five years in a growing rural market like India, thereby making the proposed system economically feasible.

8.3 Future Work

This thesis described one approach towards developing a low cost Internet access system for rural areas using satellite link; however this is neither the only approach nor necessarily the best one. Although initial cost analysis shows the proposed project is economically viable, several variations to the proposed model can be considered for further study.

The proposed system uses adaptive PSK modulation and convolutional codes. The possibility of using turbo codes can be analyzed. There are some chips available today that possibly allow high data rate transmission at a 3 dB threshold. Lowering the threshold from 6 dB proposed in in this work to 3 dB might double the number of users.

This thesis provides a qualitative description of the potential interference caused to adjacent communication satellites by the satellite in inclined GEO orbit being used for our project. A detailed quantitative analysis of the same was not possible due to unavailability of sufficient data regarding transmission power levels and CNRs used by other satellites in the vicinity of current slot of Intelsat 906 at 64^o E on the GEO orbit. Future research can look into this issue to determine specific levels of interference to adjacent satellites and calculate its effect on CNRs on uplink and downlink.

It is proposed to use commercially available circular VSAT antennas at the village stations to keep the cost of system low. However, there are some smaller uplink antennas available that are not circular – they are wider than they are high to create a narrower beam in the plane of the GEO orbit. The use of these antennas for better tracking of the satellite can be studied since they give a wider beamwidth in one plane, thereby allowing the satellite in inclined orbit to remain in the main lobe of the antenna pattern for a longer time using relatively less tracking. However, they cost more than conventional circular reflector antenna. So, the merits and demerits of both approaches can be studied to determine the feasibility of making the change.

The system proposed here operates in the Ku band using Intelsat 906 satellite. However, the system could be implemented in other frequency bands using other satellites too. In United States, full power analog television broadcasts, which operated between the 54 MHz and 806 MHz bands ceased operating on June 12, 2009 when a digital switchover was mandated. [36] At that time, full power TV stations were required to switch to digital transmission and operate only between 54-698 MHz. This opened up white space and there are future plans to offer wireless broadband services using this band. In 1975, the 800 MHz band was used as a part of a project called the SITE experiment [37] to provide instructional TV transmission to rural India. The concept was to broadcast TV transmissions using ATS-6 satellite to a central TV set in a shelter in the middle of the villages, similar to the village station described in this thesis. Although as of April 2011, TV transmission in India has not gone fully digital, it is possible that this change may happen in the near future. Once this happens, it may be possible to set up a system similar to SITE to provide Internet link from the central hub to village stations using the whitespace in TV band. This can be a topic of future research.

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