Satellite Rural Telephone Network Design: A Methodology for Performance Optimization

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(ABSTRACT)

Rural telephony has historically been a recurring subject of concern for most large developing countries. It is generally considered that rural telephone users do not generate the same level of telephone traffic and, thus, revenue as urban users, lowering the incentives to invest in rural telecommunications. The financial implications of wiring a vast area for low telephone traffic causes most telephone service providers to ignore or delay offering telephone service to those regions. Still, it is known that telecommunications are essential to the economic development of a region, and that traffic increases rapidly as soon as the service is available.

A satellite–based telephone network can provide efficient long distance telephone service to remote rural communities at a lower cost than land-based wired networks in most cases. Mobile satellite systems already provide this service, but are limited in capacity and charge high per-minute fees for the satellite link. Small earth stations and GEO satellites can provide this service more efficiently and at lower cost.

A methodology to optimize the network performance has been developed. A set of economic models to evaluate different combinations of network topologies and multiple access techniques have been implemented, and a technical-economic assessment has been performed for the different technologies under different traffic scenarios. Traffic intensity, network size and per-minute user costs have been optimized to achieve the network's economic break-even point under different conditions and constraints. The general behavior of fixed-assignment Single Channel per Carrier (SCPC), fixed-assignment Multiple Channel per Carrier (MCPC) and demand-assignment SCPC star networks, as well as demand-assignment SCPC mesh networks has been analyzed. Important parameters have been identified in order to improve the process of effective and cost-efficient satellite rural telephone network design.

Dedication

This work is dedicated to my beloved wife, partner and friend Olimpia, for following me once again into our never ending adventures in life together.

To our children Roberto, Claudia and Anamilena, who contributed so much to my well being and happiness on yet another family objective together, you will always be in my heart.

To God, for all the blessings that He has given us.

To our friends in Blacksburg, Virginia, from whom we have received and learned so much.

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Chapter 1

Introduction

1.1 Problem Statement

Rural telephony has always been a recurring subject for most large and/or developing countries. It has been known for a long time that a country's economic development (as measured by its Gross National Product, GNP) is strongly correlated to its telephone density (number of telephone lines per 100 people). This situation is more evident in countries with a vast territorial area or with a large rural population, which require a large investment in telecommunications equipment, and which need a long implementation time. It is generally considered that rural telephone users do not generate the same level of telephone traffic, and thus revenue, as urban users, lowering the incentives to invest in rural telecommunications. The financial implications of wiring a vast area for low telephone traffic causes most service providers to ignore or delay offering telephone service to those regions.

Governments, telephone companies and researchers all agree that cost is the largest hurdle [Tal98]. Studies show how bringing telecommunications to rural areas increases the indirect benefits of telecommunications investment on the economic development of that region [Hud84]. The same studies also show how actual telephone traffic rapidly increases once the service starts, often exceeding the initial projected traffic.

A satellite-based telephone network can provide efficient long distance telephone service to remote rural communities at lower cost than land-based wired networks in most cases. Mobile Satellite Systems (MSS) have been proposed for this application among others, but their intrinsic nature (circuit switched, low traffic capacity, high operational costs) has kept them away from rural telephony applications. References [Eva96], [Joh95]. [Wes94] and [Wes96] show the technical capacity of these systems, and [Con98], [Och98], [Tal98] and [Con99] show alternative solutions to this particular problem. To identify the most promising cost-effective technologies for satellite communications, [Pri96] states that "... technical feasibility, available financing and existence of a market must be present for a business to be viable," conditions which must be clearly presented in the business plan for any future satellite network.

The thesis of this research is that current satellite and earth station technology already provides technical feasibility for rural telephone systems, although this technology can and will be improved in the future to provide a better, more cost-effective service to the users. As for the market existence, over 75% of the world's population (about 4 billion people) currently has no telephone service, although that does not mean that they all can afford it. Still, the market exists for a large number of people in extended areas and rapidly developing countries. The financing required to serve them will appear when a proper business case is presented, together with the best performing technology available. This work shows how this can happen now (year 2000).

This dissertation describes a simple but efficient methodology for digital telephone network design using a computer model with variable input data for specific rural scenarios. It processes those data through a number of specific control parameters (technical constraints), and processes all data according to the desired performance parameters. This allows the designer to define the most efficient satellite system (or combination of systems) which best provides quality rural telephone and data service for optimal performance.

Initial boundary conditions for this work are based on the need to offer efficient telephone service using digital satellite systems and to interconnect to the Public Switched Telephone Network (PSTN). A variety of small, medium and large size networks of simultaneous satellite and telephone users were simulated throughout the research. Telephone circuits are assumed to be symmetrical (same amount of information flowing both ways), real time (no delays other than typical satellite propagation delay) and with standard Quality of Service (QoS) as expected from international digital voice transmission standards to access the Public Switched Telephone Network (PSTN). Typical Geostationary Earth Orbit (GEO) commercial satellites are considered for ease of use and lower operational costs, and Radio Frequency (RF) subsystems are considered standard on typical fixed, parabolic dish antenna earth stations. Finally, the absence of a terrestrial link or return channel demands this to be an autonomous, complete, bi-directional satellite system.

1.2 Research Goals

The purpose of this work is to investigate and define efficient ways to provide economic digital telephone service and data transmission to rural communities by means of a communications satellite. A detailed description and analysis of current technology is developed to fully assess the convenience of serving rural communities with current systems or the need to provide new options. An economic analysis for different technologies is presented, with emphasis on different performance parameters and its impact on total network cost, optimizing for both lowest investors and users cost.

The analysis of satellite rural telephony network designs allows the designer to look at all important aspects of network design and to investigate critical aspects of system performance. Since every desired rural network's technical, economic and social-geographic characteristics are different, it is common to have different parameters driving the network design process. Assigning a single solution to all design cases is an inefficient way to find a solution. A digital network design methodology that allows for specific parameter and performance optimization on rural telephone and data networks has been developed, allowing the designer to find the best possible technology according to the desired performance parameters.

This report also proposes a novel satellite network architecture and protocols which were developed as part of this research, that allow good Quality of Service (QoS) to remote telephone users by modifying the Asynchronous Transfer Mode (ATM) standard for digital packet communications over a high latency satellite channel.

1.3 Document Overview

This document presents a methodology for the technical and economical study of satellite rural telephone network design. It discusses the rural telephony problem and reviews past and current technologies which have been used in a attempt to provide telephone service to rural areas. Also discussed are economic indicators, performance requirements and network design techniques. It also mentions briefly a new approach to voice and data packet switched communications especially adapted to the satellite environment.

Chapter 1 presents the rural telephony problem, along with the research goals and an overview of this document.

Chapter 2 presents a comprehensive literature review on rural telephony, the fundamentals and strategies of communication systems design, reviews the initial, existing and future Wireless Local Loop (WLL) and satellite systems for this application as well as the economic issues in the design of satellite telephone networks.

Chapter 3 describes digital circuit- and packet-switched networks with an emphasis on Quality of Service requirements for digital voice over satellite channels, as well as satellite system and network performance and technology.

Chapter 4 describes the network design methodology proposed for rural telephone network design by means of optimization tools that maximize performance while providing users with a cost-effective service. Different scenarios are described and simulated for different technologies, and results are shown.

Chapter 5 describes the analysis of the results obtained in Chapter 4 and discusses their impact on telephone network design, specifically for rural satellite applications. The analysis is based on both technical factors (network size and traffic capacity) as well as economical factors (capital investment, operational expenses, revenues and user costs per-minute call). Several technical and economic parameters are analyzed and their impact on performance is optimized.

Chapter 6 shows a summary of this work, its main conclusions and contributions, and indicates potential areas for further study.

Chapter 2 Satellite Rural Telephony Background and Literature Survey

2.1 General Rural Telephone Networking Background

Remote and rural communities in large or developing countries have historically been left with poor or non-existent communications due to a number of factors, although telephone service has often been considered important for regional growth. Wireline networks are often not an economic option due to high initial investment and low financial returns, especially in small communities and isolated locations. Most current rural telephone networks exist as an obligation from governmental requirements for telephone service providers to cover low density and small remote locations. Maximum limits on mandated tariffs are often imposed, so the economics of those rural nodes have been subsidized either by the government or by urban users.

Wireless communication networks are gaining an increasing amount of attention for use in such applications due to more cost-effective performance. Although analog Multiple-Access Radio has been used before in rural applications, new wireless digital systems could help bring telephone communications to remote locations through the use of Wireless Local Loops (WLL) as mentioned by [Cox96], [Pad95] and [Wes96]. Since wireline service operators may not serve remote locations, high- and low- tier WLLs can provide a wireless "last-mile", but it still requires long distance access to the PSTN. This can be achieved with a satellite terminal, which has ubiquitous presence under the satellite's footprint. For that reason satellites are being considered as either a relay service (hybrid bent-pipe) or as part of an integrated cellular / satellite system, as reported by [Re95], [Eva97], [Con99] and [STM99].

2.1.1 The Rural Telephony Problem: Local and Long Distance Communications

Rural communities without telephone service have two different problems: they can neither call their neighbors (local calls) nor the outside world (long distance calls). If a rural village has at least a single long distance telephone line placed at the local store, authority or health facility, local people can at least communicate with relatives, authorities or other government offices. The calls may be for personal, emergency or important official messages, even if users have to walk to this place. Although many countries mandate their local telecommunications operators to provide long distance telephone service to certain size communities, these mandates are often ignored or delayed because of economic factors.

A rural village will hardly have local service if they do not have long distance service, which has higher priority. Local telephone service will usually be implemented in villages that reach a certain minimum size and telephone traffic conditions, and only after long distance service has been operational and people are familiar with its use. A local network not connected to the Public Switched Telephone Network (PSTN) is called a private network. The local network's transmission media between the switch and the local user's premises is called the "last mile technology", and it may consist of cabled (wired) or radio (wireless) communication links.

Local calls are handled by a local switch office, which connects calls from one villager to another rural subscriber according to the number dialed. If a long distance number is dialed, the local rural office will switch the call to the long distance switch, or gateway, which will connect the call to the long distance transmission system and carry the call to another gateway connected to the PSTN. Thus, the long distance gateways are the most important elements of the telephone network regarding rural telephony. It is the intention of this work to show that a satellite system can provide rural telephone service with a good Quality of Service (QoS) using a digital communications network. Special attention is drawn to the remote (rural) and gateway (urban) earth station elements and overall satellite network technology that provides long distance telephone service using Very Small Aperture Terminal (VSAT) technology when following a cost-efficient design methodology.

2.1.2 Design of Rural Telecommunications Networks

There are many issues to be defined when designing rural telecommunication networks, all of them of varying importance, but almost all of them fall into three main areas: geopolitical, technical and economic. Geopolitical issues deal with the rural region's developmental level based on its social, political, educational and economic history, which is important to define but will not be covered in this work [Sch96]. Technical issues usually refer to available technology, regulatory and legal frameworks, rural communities’ size and expected communications traffic, type of communication services and available technical workforce [Con94]. Economic issues deal with defining the initial investment required to deploy communications equipment in a remote region, its operational cost and the users' revenue generating capacity, so the service is self-supported financially and keeps subsidies to a minimum.

The latter analysis must include both the cost of available technology, initial and future expected traffic and the performance metrics and technical standards required by the national telecommunications networks or PTT operators. It is in these two areas, technical and economic, where the present work is situated.

Although the design and specification of technical elements in communications networks fall almost entirely into the telecommunications engineering area, and the economic analysis of the network is a mainly a finance problem, the proper network design sequence and future economic success depends heavily on another engineering branch, called systems engineering.

2.1.2.1 The Life Cycle Process

The systems engineering process provides a way to better understand and approach most design problems over the complete life cycle of a product, in this case a rural telecommunications network. It provides the methodology to efficiently manage any given man-made system, from the conceptual design to the termination and disposal stages [Bla98]. Based upon this approach, the design of any communications network must include the steps shown in Figure 2.1

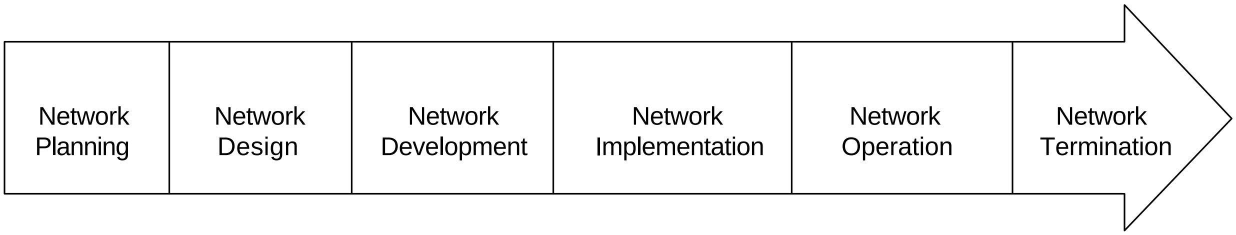


Figure 2.1. The systems engineering life cycle process.

The sequence of technical and economic activities required to design a satellite rural communications network are complex processes that should be achieved by many people in different areas of expertise and at different times, working as a team, following a system management plan and supervised under a single authority. The key for the systems engineering process' success is good planning, good management and teamwork.

The technical scope of the present work is only at the network design stage; thus the rest of the technical process is to be done elsewhere. On the other hand, the economic scope of this work must include all steps shown in Figure 2.1 in order to provide investors with a clear idea of all major financial milestones.

1. *Network Planning Stage:* This refers to the basic identification of rural telephone needs, dimensioning of the networking problem and definition of possible solutions.
2. *Network Design Stage:* This refers to the search for real and feasible solutions once the basic needs have been identified. The input information must be processed with whatever technical and economic constraints exist, and optimal solutions are delivered.
3. *Network Development Stage:* This refers to the necessary steps to develop the network elements as defined at the design stage. Includes the logistics to acquire, assemble and deliver systems and subsystems, personnel training and testing.
4. *Network Implementation Stage*: This refers to the construction of the network following the previously defined logistics plan by transporting the equipment to its final destination, assembly of systems and subsystems at each site, testing each terminal and local network, and training of local operators.
5. *Network Operation Stage:* This refers to the use of the communications network by rural users, as initially specified at the conceptual stage. It actually is the delivery of the end product to the consumer, in this case digital telephone service to rural users, and it should last throughout the expected equipment life cycle. It is also during this productive equipment's lifetime that it will generate revenue to network operators and investors, as defined in the network design stage.
6. *Network Termination Stage:* This refers to the retirement of equipment after it has reached its operational lifetime. Aging, new technology availability, frequent equipment malfunctions or high operational costs may be the cause. New regulations show increasing concern to dispose of old products in an environmentally friendly way.

2.1.3 Wireless Local Loops (WLL) for Rural Local Communications

Currently, wireless technology offers different networking options for local loop telephone applications, not considering point-to-point or point-to-multipoint radiotelephones. Digital wireless telephone technology can be divided into two very well defined groups, based on its technology platforms, services and characteristics. 1) *Cordless telephone systems*, which are also defined as Low-Tier Wireless Local Loops (L-WLL), and 2) *Cellular telephone systems*, which are also defined as High-Tier Wireless Local Loops (H-WLL). Since both WLL groups work at UHF frequencies, rain is not a problem, and for rural, scattered, semi-fixed users, multipath is not as big a problem as it is in urban applications.

Cellular (high-tier) communications allow wireless telephone service, but coverage is usually limited to urban and suburban areas. Cordless (low-tier) communications can now offer this service, too, but the coverage area is even smaller than that of cellular systems. In both cases, satellite access to the PSTN Central Office (CO) switch is needed for remote site applications. Either type of technology could provide adequate service in a remote Wireless Local Loop application if there is a satellite link to the PSTN.

Personal Communications Systems (PCS) is a term often applied to cellular telephone systems, although PCS and cellular are not exactly the same. Certain bands of frequency have been assigned for cellular service (450-470, 824-849 and 869-894 MHz), depending upon the country and technology being used. On the other hand, frequency spectrum around 1900 MHz has been assigned to PCS, consisting of three blocks of 30 MHz each and three more blocks of 10 MHz each, including forward and reverse bands. The bands from 1850-1910 MHz and 1930-1990 MHz are reserved for licensed operations, while the band in between (1910-1930 MHz) was assigned to PCS unlicensed operations [Rapp96].

The main difference between cordless (low-tier, L-WLL) and cellular (high-tier, H-WLL) systems is the coverage area, which in the first case is usually a few hundred meters for low mobility users, while in the second case the area may be a few kilometers for high mobility users. Each WLL technology also has specific characteristics regarding traffic capacity and performance depending upon the network size, and will be briefly described next.

2.1.3.1 High Tier (Cellular) WLL

A high tier WLL is basically a cellular radio mobile system which provides a wireless connection from the user's terminal (portable, mobile or semi-fixed) to the PSTN through a radio channel. Current cellular systems are known as *Second Generation*, since they are the digital evolution over the analog *First Generation* cellular systems. New developments in technology will bring what is being called *Third Generation (3G)* systems, a further evolution on current (2G) cellular systems that allows higher bit rates, able to serve data services such as the Internet.

The three most important 2G digital cellular standards are known as GSM, CDMA and TDMA. The first, Global System for Mobile or GSM/DCS1800, is a European standard and currently the most widely used digital cellular and PCS standard in the world. The second, using Code Division Multiple Access or CDMA/IS-95 is a U.S. standard introduced by the company Qualcomm, and the third, using Time Division Multiple Access or USDC/IS-136, is an evolution of the first generation AMPS system and also a U.S. standard. The main parameters of the 2G H-WLL systems mentioned above are presented in Table 2.1.

Table 2.1. High tier wireless local loop technologies

Cellular standard		*IS-54/136*	*GSM*	*IS-95*	*DCS 1800*
Multiple Access		TDMA/FDMA	TDMA/FDMA	CDMA/FDMA	TDMA/FDMA
Freq. Bands	Fwd	869-894 MHz	935-960 MHz	869-894 MHz	1805-1880 MHz
	Rev	824-849 MHz	890-915 MHz	824-849 MHz	1710-1785 MHz
Modulation		$\pi/4$ DQPSK	GMSK	BPSK/QPSK	GMSK
RF Channel		30 kHz	200 kHz	1250 kHz	200 kHz
Carriers per channel		3	8	Variable	8
Channel bit rate		48.6 kbps	270.833 kbps	1.2288 Mchip/s	270.833 kbps

2.1.3.2 Low Tier (Cordless) WLL

Low tier WLLs are currently the high-end evolution of indoor cordless telephones, which now feature digital services and allow more extensive coverage area than their predecessors. Frequency spectrum has been assigned to L-WLLs around 1900 MHz in most countries. In order to solve the last mile problem for the PSTN they are expected to cover only a neighborhood area, thus limiting fast-moving phones. L-WLLs could be used for large concentrations of users in small areas with low user mobility, such as pedestrians or home users in urban or suburban locations.

Arguably the three most promising digital standards in the world are mentioned next. First, the Personal Access Communications System (PACS), a U.S. system designed to merge with the

Integrated Services Digital Network (ISDN). Second, the Digital European Cordless Telephone (DECT), a European system with a new PCS version (PWT) proposed for its use in the U.S.; and third, the Personal Handiphone System (PHS), a highly successful Japanese system. Table 2.2 shows the basic parameters of each technology.

Table 2.2. Low tier wireless local loop technologies

Cordless standard	*PACS*	*DECT / PWT*	*PHS*
Multiple Access	TDMA/FDMA	TDMA/FDMA	TDMA/FDMA
Frequency (MHz)	1850-1910 1930-1990	1880-1900	1895-1918
RF Channel (kHz)	1728	300	300
Number of carriers	16 pairs/10 MHz	10	77
Channels per carrier	8/pair	12	4
Channel rate (kbps)	32	32	32

2.2 Satellite Communications Background

In 1945 Arthur C. Clarke [Cla45] showed that a man-made radio repeater placed over the equator at 42,164 km from the center of the earth would have an orbital period that matched the earth's period (23hours 56 minutes). At this altitude the satellite would seem to be stationary to an observer on earth, thus allowing it to be used as a permanent radio repeater covering almost 42% of the earth's surface. This orbit is called the Geostationary Earth Orbit (GEO). Three GEO satellites in the same orbit placed 120 degrees apart could provide radio relays to almost the entire world. The USSR launched the first artificial satellite, Sputnik, in 1957. In 1958 the U.S. launched Score, the first satellite to transmit a recorded voice message, and just like Sputnik, it was placed in a Low Earth Orbit (LEO).

The first satellite to reach GEO orbit was Syncom II, launched by the U.S. in 1963. Since then, a large number of communications, earth observation and military satellites have been put in different orbits, depending upon the specific application. Most communications satellites have been placed in GEO orbits, but recently new global satellite systems have been using a large number of LEO satellites in inclined orbital planes in order to provide service to the entire world. This is called a *satellite constellation*.

2.2.1 Satellite Communications Concepts

All satellite communication systems have two segments: the ground segment (earth stations) and the space segment (communications satellites). The ground segment may be further divided into two main elements: a transmit earth station and a receive earth station. There may be any possible combination of these elements: a single transmit/receive earth station operating on a closed loop, one transmit and many receive earth stations (broadcast), or any number of transmit/receive earth stations forming a satellite communications network. A network may be connected into a number of different topologies, depending upon its main application and technical requirements. Since the early 1960's the development of satellite communications has been impressive in terms of capacity as well as in performance.

2.2.1.1 Satellite Communications Theory

Any satellite follows a trajectory that is defined by its distance from the center of the earth, as described by orbital mechanics theory. The physical and mathematical basis for orbital mechanics were described by Newton and Kepler centuries ago, but only in recent times did technology allow high altitude launches and the use of electronic communications systems.

Newton's Universal Gravitational Law describes the force and velocity required for a body to stay in orbit, while Kepler's three laws describe the geometry and trajectories of celestial bodies. The general case for Kepler's laws applies to elliptical orbits but a circular orbit may be considered as a special case where both foci are at the same position. The period of an orbit of any satellite is described in [Pra86] by:

$$T^2 = \frac{4p^2a^2}{m} \tag{2.1}$$

Where T = orbital period (seconds), a = Distance between satellite and center of the earth (km), and μ = Kepler's constant (μ = 3.9861352 x 10^5 km^3/s^2)

If the satellite orbital period equals the earth's rotational period, the satellite is in a GEO orbit, located at 42,164 km over the equator. If the satellite's orbital period is much shorter than earth's, it follows a Low Earth Orbit, but requires a higher velocity to avoid being pulled down by the earth's gravity. If the satellite's orbital period is longer than earth's, then it follows a High Earth Orbit (such as the moon) and a much lower velocity is needed to maintain orbit.

The distance to the satellite is very important in telecommunications for two reasons: signal attenuation and time delay. *Free Space Attenuation* is the loss of radiated signal power as it moves away from the transmit antenna due to spherical spreading. A long propagating distance results in low signal power density per unit area. Additional attenuation occurs in the atmosphere due to interaction of the signal with atmospheric gases during propagation. *Delay* is the time it takes for the signal to travel from one point to another at the speed of light. GEO satellites are placed so far from earth that it takes over one quarter of a second to relay a signal between two earth stations. This delay can be significant in certain cases such as real-time voice and video, as well as in some data transmission applications.

2.2.1.2 Satellite Communications Model

What makes a communications satellite different from other satellites is its payload, usually a radio repeater consisting of a transmitter/receiver combination called a transponder. The long path between an earth station and a satellite causes high losses (attenuation) especially at higher frequencies, therefore amplifier gain must be provided for the carrier signal in order to overcome this problem, and this is the transponder's task. A typical bent-pipe transponder consists of 5 main elements:

1. Receive antenna
2. Front end receiver (mainly a Low Noise Amplifier = LNA)
3. Frequency converter
4. Transmitter (mainly a High Power Amplifier = HPA), and
5. Transmit antenna, which may be the same as the receive antenna (element 1).

While the antennas provide passive gain, the LNA and HPA must provide active (electrical) gain to the signal, enough to overcome the path losses. Extra losses are often taken into consideration, especially rain fades and interference losses. Earth stations typically consist of elements 1 and 2 mentioned above (receive earth station) and 4 and 5 (transmit earth station), which are used for the same purpose. The end-to-end signal power budget, called a link budget, is described in (2.2) in dB units as

$$C/N\,(dB) = P_t + G_t - L_p - L_r + G_r - k - T_{sys} - B \qquad (2.2)$$

Where

C/N = Received signal's carrier to noise ratio (dB)
P_t = HPA's transmitter power (dBW)
$G_{t,r}$ = Transmit and receive antenna gain (dBi)
L_p = Propagation loss (dB)
L_r = Rain loss (dB)
k = Boltzmann's constant (-228.6 dB-J/K)
T_{sys} = System noise temperature (dBK)
B_N = Receiver Noise bandwidth (dB-Hz).

The total C/N figure is based on the combination of numerical (ratio, not dB) values of the uplink and downlink C/N figures plus an interference ratio C/I, as shown next

$$\left(C/N \right)_t = \frac{1}{\dfrac{1}{\left(C/N \right)_u} + \dfrac{1}{\left(C/N \right)_d} + \dfrac{1}{\left(C/I \right)}} \qquad (2.3)$$

Once the signal is guaranteed to provide a good carrier to noise ratio, demodulation provides the required Energy per bit to Noise density (*Eb/No*) ratio, described as

$$Eb/No = C/N + B - Rs \qquad (2.4)$$

Where Rs is the symbol rate in dB-symbols/second.

When more than one signal is sent to the satellite, there must be an organized way to accommodate each carrier, so channels are divided and used according to a pre-defined multiple access scheme, which heavily influences the satellite network's bandwidth efficiency and throughput. Multiple access protocols are classified by [Pey99] into several types: fixed assignment, demand assignment, random access, hybrid random access and reservation, and adaptive protocols.

Fixed assignment protocols are good on high traffic, small (few nodes) networks. Demand assignment protocols are better suited to low traffic, larger networks, such as satellite rural telephony. Random access protocols are mainly used to transmit medium traffic data in packet networks, while hybrid random and reservation protocols work best at medium traffic data packet networks with occasional higher traffic by just one or a few of the nodes at any time. Finally, adaptive protocols allow completely random access for low traffic and change dynamically to reservation for higher traffic loads.

2.2.2 Basic Repeater (Bent-Pipe) Satellite Systems

As mentioned before, what differentiates a communications satellite from other satellites is its repeater payload, a number of radio receivers/transmitters that are better known as *transponders*. A transponder is a communications repeater for radio signals received on board the satellite, processed and then transmitted to a ground earth station. A transponder is generally defined by its bandwidth capacity (36, 54 or 72 MHz on Ku-band satellites), its available transmit effective isotropic radiated power (40 dBW to 54 dBW or 10,000 W to 250,000 W) and its on-board processing capabilities.

Early transponders were simple and consisted of only a few subsystems: receiving and transmitting antennas, a Low-Noise Amplifier (LNA) receiver, a frequency converter and a High-Power Amplifier (HPA) transmitter. This basic (and still very popular) type of transponder would only receive the signal through the Rx antenna, amplify it in the LNA, change the frequency (down convert) and feed it to the HPA, and then transmit it through the Tx antenna. Since no change is made to the signal, except for carrier frequency translation and power amplification, a satellite with this type of transponder is also known as repeater (or bent-pipe) satellite.

A traditional repeater satellite is complex in the sense that several effects can take place in the received signal (non-linearity, delay, distortion), but always regarding its frequency and power, not the signal content itself, so the transponder never "knows" anything else about the signal. A bent-pipe transponder is almost transparent to the user since it sends back basically the same information, and in the same sequence, as it arrived, thus "repeating" the signal. That has been sufficient for past and most current satellite applications, but may not be enough for digital packet satellite networks. Figure 2.2 shows the basic arrangement for a bent-pipe satellite link.

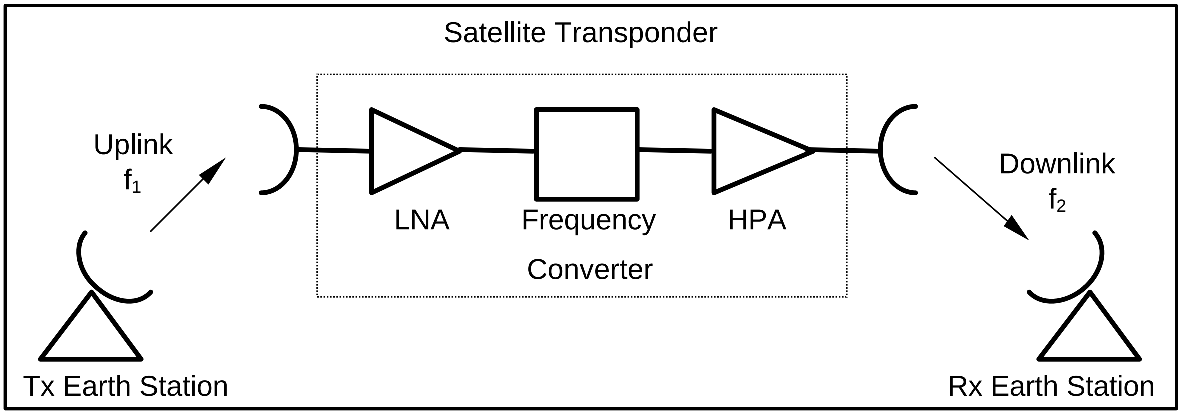


Figure 2.2. Basic repeater (bent-pipe) satellite link elements.

2.2.3 Advanced On-Board Processing (OBP) Satellite Systems

As mentioned above, a repeater satellite only changes frequency and power parameters on a digitally modulated, but still analog, signal. That means that if there is distortion on the uplink analog signal, this distortion will be amplified and translated in frequency to the downlink, thus lowering even more the quality of the analog signal. This has a negative impact on the received downlink signal power and total C/N ratio, as described on equations 3 and 4. This has a direct effect on the digital signal's bit error rate, and neither the user nor the repeater satellite can improve that signal, although coding may help.

A repeater satellite also forces the signal to follow the same route; from the receiver to the transmitter all signals on that specific transponder will always be together, coming from the same transmit earth station and going to the same receiving earth stations. That is a limiting factor in some networking applications, where versatility to switch is needed to offer a better service.

Due to these limiting factors on basic bent-pipe satellites, new type of transponders were conceived, which allow a number of different approaches to avoid these problems, although none is currently able to solve all of them, since the limitations are different for each application. These types of transponders are used on "smart" satellites called On-Board Processing (OBP) satellites, since they process in various ways the uplinked signals before repeating them on the downlink.

One type of on-board processing, called base-band (BB) processing takes place by downconverting and demodulating the analog signal, then demultiplexing and reconstructing the binary information stream to correct any errors that may have happened during the uplink. A new rectangular pulse waveform is generated with the clean binary sequence and, after that, the signal is again modulated, multiplexed and upconverted to be transmitted on the downlink, clean from any uplink degradation, thus improving the Eb/No ratio and, therefore, the BER at the receiving earth station.

Another type of OBP takes place when many Time Division Multiple Access (TDMA) signals from different transmitting earth stations are received at the satellite, then are base-band processed into binary streams and multiplexed into a single TDM signal going down to a single receiving earth station. This earth station usually acts as a hub or gateway into a single computer or network in a star topology, thus optimizing the satellite's power and bandwidth for the downlink.

Two other common types of OBP are increasingly taking place on satellite systems involving some type of on-board switching: spot beam switching, and packet switching and routing.

Spot-beam switching involves the use of several receive and/or transmit antennas (or directive beams) onboard the satellite, which are used to send information to selected regions (spots) as seen from the satellite. This allows the reuse of the same frequencies for different coverage areas, thus increasing satellite capacity, as long as the spots are sufficiently far apart from each other to avoid interference. The satellite would have to "know" to which spot the incoming signal must be sent, or the other way around, usually by the use of certain link frequencies or by reading the packet's address. This is a very effective way of routing specific-site or point-to-point links.

The other type of onboard switching involves the use of the satellite as an "intelligent" network node. It will be mentioned later how packet networking architectures such as ATM and TCP/IP require the packets to follow a certain path or route to its terminal node, as included in the packet overhead (or address) during the connection period. The process of routing is done by a cross-connect device called a "switch". Each switch has a number of input and output ports, which are connected to other ports at different switches across the network according to a connection plan stored in memory, also called a "routing table". There, the switch reads its virtual connection parameters and sends the packet to the physical channel through the proper output port.

Broadband satellite networks are developing on-board processing technology that allows the use of the satellite as a network router, or as they call it, a "Switch in the Sky", which will allow faster routing and forwarding. A number of experimental and commercial satellites have been using switching technology for some time, like Italy's ITALSAT and European OLYMPUS satellites as well as NASA's Advanced Communications Technology Satellite (ACTS) [Had99].

Since satellites can reach longer distances, it is expected that less processing time will be required (only one router/switch) with the possibility of lower latency, although propagation time on satellite networks will still play a significant role in overall latency. Another advantage is that an OBP satellite will be able to re-direct packets into the correct spot beam, time frame, downlink frequency or sub-network, either for a single user or for broadcast, at -and from- any point where a satellite's extensive coverage area allows.

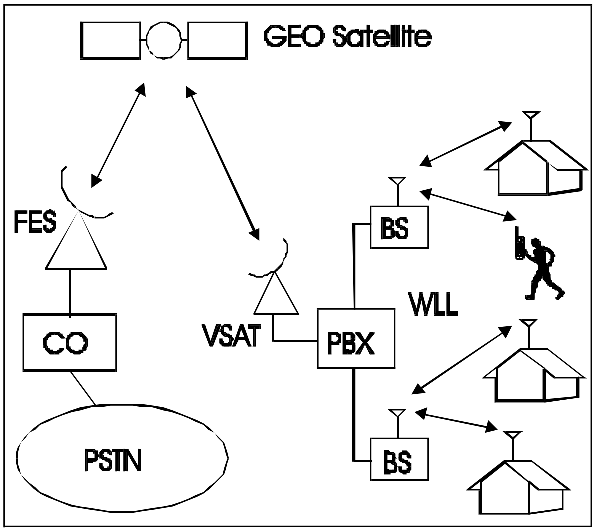
2.3 Satellite Systems Used for Rural Telephony

Rural Telephony by satellite has been widely studied and described, but in fact much of that work never became a reality until recent times for several reasons. There were a few places where it had been implemented before, usually on small pilot networks as mentioned in [Ros81] and [Con94]. Recent large applications are currently being deployed in South Africa (3,000 small terminals), Guatemala (600) and Australia (400) as reported in [Gil99]. There have also been large network implementations in Chile (1,700) and Peru (190) as detailed in [Com99], but large VSAT manufacturing companies and telephone service providers are still looking for cost-efficient designs, attractive for all involved (manufacturers, operators and service users).

Several satellite system technologies can be used in rural telephony, requiring different analysis of technical parameters. The satellite network's technology heavily influences the user terminal (small earth station) characteristics as well as its overall costs. Typical uses of small or personal satellite terminals are

- Serve coverage areas without wireline or cellular service,
- Replace telephone networks in disaster situations, or
- Serve as an auxiliary buffer when the wired or wireless capacity has been reached.

A remote user can access the PSTN via satellite in one of two ways: through an indirect user link access to the satellite, or a direct link access. The indirect access to the satellite is made from a wired or Wireless Local Loop (WLL) user terminal through a VSAT terminal and a GEO satellite *(hybrid system,* Figure 2.3*)*. The direct access architecture allows the user to transmit from a mobile terminal directly to the satellite *(integrated system,* Figure 2.4*)*.



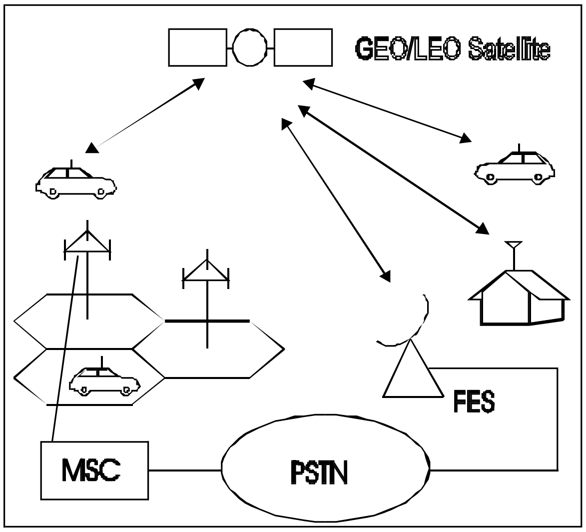


Figure 2.3 Hybrid satellite system

Figure 2.4 Integrated satellite system

2.3.1 First rural satellite systems

The first telephone links via satellite were implemented during the 1960’s for international long distance links among very large (30 meter) earth stations in several countries, mainly to interconnect their national telephone networks, but rural telephony was not economically attractive at that point. Rural satellite systems were eventually implemented later in satellite history in developing countries such as Nigeria and Sudan through the support of the International Telecommunication Satellite Organization (*INTELSAT*), which helped provide telephone service during the 1970's. Most of the early work involved the use of the INTELSAT *VISTA* network, which included the use of INTELSAT satellites and small earth terminals especially designed for rural telephony [Ros81]. Although the system was technically good at that time and did fulfill its goal, it was an expensive and limited solution for most countries. Nevertheless the old VISTA concept has still been an important service at Intelsat and rural telephony satellite systems have been improving thanks to better and lower cost satellite and earth station technology [Alb93]. Other countries such as the U.S. (Alaska), Canada, Australia, Mexico, India and Indonesia have since benefited from their domestic satellites for rural communications. Other countries such as South Africa, Chile and Peru have benefited from international (INTELSAT, PANAMSAT) or leased domestic and commercial satellite capacity for rural telephony. The technology used in each case has been mainly through small earth stations with telephone interfaces that allow interconnection to the PSTN over a typical GEO satellite at either C or Ku band. Most rural satellite service is still subsidized at some point.

2.3.2 Mobile Satellite Systems (MSS)

Early satellite systems used fixed-antenna earth stations with narrow antenna beams, where a parabolic dish ground station antenna was pointed towards the GEO satellite. This allows the placement of many satellites a few degrees apart from each other to avoid interference. The earth station must have a directional antenna, which cannot be used for mobile (cars, trains, ships or airplane) communications.

Departing from the initial fixed-earth station application, during the mid 1970's a global satellite communication system for US ships, *MARISAT*, was developed to provide voice and data communications to ships on the high seas using L band frequencies (1.6/1.5 GHz) with small, directional and omnidirectional antennas. By the end of that decade an international consortium was created under the name *INMARSAT*, which included MARISAT and the European MARECS satellites, offering commercial service to maritime, terrestrial and aeronautical users. INMARSAT uses small, portable terminals for voice, low bit rate data and fax for vehicle and ship-borne applications on a global basis through a gateway earth station connected to the PSTN or public data networks. Other mobile communication satellite systems were later created using GEO satellites at L band: *MSAT*, a US/Canadian joint venture; *Optus*, an Australian system, and *Solidaridad*, an INMARSAT-like Mexican system [Con94].

More recent systems include the use of multiple Low Earth Orbit (LEO) satellites such as *Iridium*, a 66 satellite system developed by Motorola for voice and paging services, operational since the end of 1998 at L band, but later put out of business. *Globalstar,* a 48 satellites system developed by Loral Qualcomm for voice and data services at S and L bands (2.5/1.5 GHz), already deployed and operational, but allegedly in financial trouble since the service launch. Other systems are also being developed at this time, although the initial excitement for global mobile satellite services has seriously slowed down.

2.3.3 VSAT-Based Rural Satellite Systems

A Very Small Aperture System (VSAT) satellite network consists of a Master Earth Station (Gateway, Hub) which controls a number of smaller remote earth stations allowing digital transmission through a number of possible networking combinations, usually in a star or mesh topology. The remote terminals are known as VSATs (Very Small Aperture Terminals) because they have small antennas. VSATs were originally developed during the early 1980's for business data transmission between remote sales offices or branches and its mainframe computer or communications center [Gil91]. They have been heavily used for retailing, banking, financial and parts distribution companies' data networks operating as multiple sites in large regional or national systems [IEEE88], [Gil95].

A VSAT terminal usually includes a 0.6 - 2.4 meter dish antenna and a transceiver radio (outdoor unit - ODU) and a set of baseband and IF subsystems (indoor units - IDU). It requires electrical power, which in some locations could mean solar panels and battery banks, as well as some kind of fixed shelter for harsh environments. In hybrid architectures the VSAT is connected to the WLL base station or radio port and to the local switching exchange.

Examples of rural telephony systems, some of them hybrid, are those offered by Gillam (Belgium), Gilat (Israel), and Titan, Scientific Atlanta, STM Wireless and Hughes Network Systems in the US [Com99]. These systems provide local wireless service plus a GEO satellite terminal for long distance access to the PSTN in a networked environment. The users only require a common wireless phone since the service provider or network operator provides the VSAT terminal. The satellite frequency spectrum required for these systems might be that of any available C or Ku band transponder that services the coverage area, but the local WLL frequency spectrum, cell size and distribution and required radio power have to be defined and approved locally. Most systems include solar cell powered equipment for remote rural communities if needed.

Gillam manufactures the *SATELNET* product [Gill99]. Gilat manufactures the *DialAway* and *FaraWay* products [Gila99], [Com99] part 1.1.1. Scientific Atlanta manufactures the *Skylinx* product [SA99], while Hughes Network Systems (HNS), developed its *Terminal Earth Station (TES) Quantum* and later its *TES Quantum-Direct* products [HNS99]. STM Wireless, Inc.

manufactures the *DAMA 10000* and the new *SpaceLoop* network [STM99]. And finally The Titan Corporation manufactures the *Xpress Connection* [Tit99]. Most of these systems have had mixed economic success, and the market is strongly divided between Gilat and HNS [Com99].

2.3.4 Broadband Satellite Systems

The Internet explosion has created a global demand for wideband data services that cannot be met by current wireline terrestrial networks only. Cellular and other current wireless systems do not have the capacity to provide wideband services either. A new technology, Local Multipoint Distribution Service (LMDS) will be able to provide this service in urban and some rural communities, but its reach is still limited. Satellite systems have entered the broadband communications arena through the use of different technologies, such as Direct Broadcast Satellites (Hughes's dual DirectTV and DirectPC). VSAT technology is also being used for this application, mainly through similar systems offered by the same companies mentioned above (Gilat, HNS, STM Wireless, S-A) and others such as ViaSat, Datel, Norsat and Wireless World Wide Web (W4). Most of these VSAT-based systems already offer a rural or remote high speed (64 kbps to 2 Mbps) satellite connection to the Internet through various hub gateways and operate on a star topology at Ku-band with antenna sizes between 0.8 and 2.4 m.

In a different area, but following upon the promise of the mobile communication satellites and expanding its limited bandwidth capacity, a number of companies are developing broadband mobile satellite systems at both LEO and GEO orbits in order to provide broadband multimedia-capable digital services at a global level. These networks will be able to provide Broadband Integrated Services Digital Network (B-ISDN) channel capacity and high-speed IP and ATM packet switching services to every corner of the earth. The only part of the RF spectrum with available bandwidth for these applications is Ka band (30/20 GHz), so most broadband satellite systems are planning to use that frequency band.

One such system, *Teledesic*, is based on an on-board ATM packet switching format through a constellation of 288 LEO satellites at Ka band and is expected to start operations by 2004 [Tel99]. Another system called *Spaceway,* proposed by Hughes Network Systems (HNS), consists of 8 GEO satellites with advanced on board processing and regeneration capacity operating at Ka band, expected to be operational by 2002 [Spa99]. *Astrolink* is a new system proposed by Lockheed Martin, TRW and Telespazio based on the use of 9 GEO satellites scheduled to begin operations in 2003 [Ast99]. *Skybridge* is a system proposed by Alcatel, based on the use of 80 LEO satellites at Ku band, expected to be operational by 2002 [Sky99].

2.4 Economic Issues in the Design of Satellite Rural Telephone Networks

As mentioned in Section 2.1 above, the design of rural telecommunications networks mainly involves two main areas: communications engineering and economic planning. Since both areas are important, the first part of the network process involves a joint collaboration, where both engineers and economists will work together to try to dimension the real telephone needs for a certain region and offer a technically and economically feasible solution. This will allow an intelligent choice of technology regarding system capacity and cost-effectiveness.

All components, systems and subsystems of the proposed network have an associated cost, and its continued operation will also generate expenses throughout the system's lifetime. On the other hand, the system's operation will also generate revenue, allowing these costs to be recovered with the network's usage during the system's lifetime. Costs should be kept to a minimum while still providing quality service to the users, and revenue should be maximized while still charging a low usage cost. This is not an easy balancing task, so every aspect of the network's cost and usage must be carefully analyzed, for a small input parameter change could make a large output difference and possibly define the project's economic success or failure. Next, the most important issues when designing a satellite network, in this case for rural telephony applications, will be presented.

2.4.1 Rural Telephony Economic Issues

As mentioned above, the design of a rural telephone network involves collaboration between engineers and economists. For the engineers, this means gathering geographical data, considering the location, number and size of all potential communities and looking for available technologies that could provide such service. Another need is to assume within some limits the amount of expected local and long distance traffic for the separate nodes, and narrow it down to a cautiously reasonable figure. If there is interest or the need to provide a different type of communications service (data, video, fax, Internet access), this should also be considered in the traffic and system capacity analysis, along with the proper network interconnection. At this point all cabled, fiber optic, radio and satellite options must be evaluated in order to define the best technology that allows interconnecting the remote sites to the Public Switched Telephone Network (PSTN) or any other desired network.

The previous network design experience of engineers involved in this stage is very important in order to eliminate obviously inappropriate or inefficient technologies according to the specifics of the situation. Two typical examples of inefficient use of technology would be the use of fiber optic cables on a large number of dispersed small villages in mountainous terrain, or the use of satellite systems in a community within a few miles from a large city. A network topology (star, mesh, tree or bus) has to be defined after determining the total number of nodes in order to provide the most efficient access to the desired network. Once the service has been defined as a viable option, a technical-economical analysis will define one option over the other technologies. If a satellite network is found to be the most attractive solution, then the satellite network design process begins.

The work that economic planners must do is different, since it involves many economic aspects of the network in order to make a business case out of it, otherwise the project will never take place. The first element of data that must be found is the expected telephone service demand or number of calls per unit time and expected call length in minutes. That is known as traffic, and is important since that will be the single most important factor for determining revenue and, thus, the profitability of a network. Second, there must be an evaluation of the existing market, that is, the rural community’s interest for the service and its economic purchasing or spending power, both of which should provide guidance for a financially healthy business.

Once the network has been defined along with the engineers, the economists must make a cost analysis of the network life cycle process, its development and implementation costs as well as its operational life and retirement costs. That should include both the terrestrial and the space segments along with maintenance and other operational expenses. They must then define the expected revenue from the network’s usage, and also extend the analysis over its lifetime in order to learn about its profitability over time.

2.4.2 Multiple Access and Topology Evaluation Techniques

Multiple access is the process of optimizing the resources on a communications network, in this case the satellite channel, when many earth stations try to communicate through it. Depending on the network configuration, and especially on the expected earth station traffic, the channel may be available to every one at all times (fixed assignment), to just a few who ask for it (demand assignment), or to those who grab it by random access when it’s needed (contention assignment).

Different applications require different types of multiple access, depending upon the type, quantity and limitations of the information to be sent. High volume and high traffic applications usually require fixed assignment at all times, while short, bursty applications are more efficient on contention assignments. Demand assignment is somewhere in between, when a channel may be needed for a large volume transmission but only for some time, releasing the channel once it has finished using it.

2.4.2.1 Multiple Access Techniques

There are different types of fixed assignment (or basic) multiple access protocols:

- Frequency Division Multiple Access (FDMA), where each earth station is allocated a specific frequency and bandwidth on the satellite’s transponder at all times and no one else can use it, even when the frequency is idle.
- Time Division Multiple Access (TDMA), where each earth station is allocated the whole transponder bandwidth but only for a specific amount of time in a sequence, called a time slot.
- Code Division Multiple Access (CDMA), where each earth station may use the whole transponder bandwidth all the time, thus interfering with each other, but is assigned a specific orthogonal binary code so that only the desired receiving earth station can recover the transmitted information.

Figure 2.5 shows the general taxonomy of multiple access protocols typically used in satellite communications, with an emphasis on the protocols used in this work.

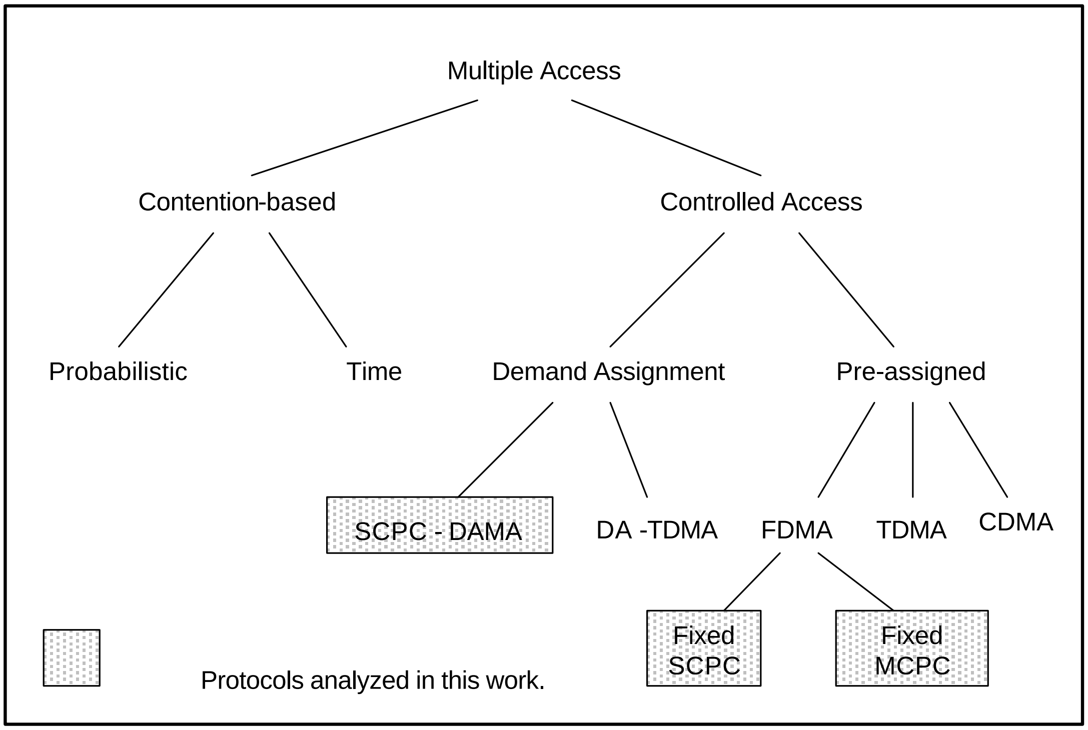


Figure 2.5 Taxonomy of multiple access protocols for satellite communications

There are several advantages and disadvantages to every type of fixed multiple access, and that makes them useful for specific situations depending upon the network configuration, topology and type of transmitted information.

The selection of a multiple access protocol should consider the specific bandwidth and power availability and communications requirements at both the transponder and the earth stations [Bha81], [Pra86], [Rod96]. Any communications satellite is basically subdivided into several transponders with different frequency bands, which is a rough type of FDMA. Any type of multiple access can be used on a transponder.

The main advantage of fixed assignment multiple access is that the channel is always available when the user needs it, but it also creates expense due to transponder bandwidth or time usage, even when it is not in use. For low traffic applications that may not be a sound business idea, so demand or contention assignment are usually recommended. Demand assignment is usually used for medium to low traffic, longer duration applications, such as voice telephony, while contention assignment is widely used for short, frequent data bursts such as in data and Internet transmissions.

Probably the most important demand assignment protocol, known as Demand Assignment Multiple Access (DAMA), is related to both time or frequency assignment demand. Frequency demand usually takes place when a single earth station requires the use of a single channel to communicate with another earth station, and is known as Single Channel per Carrier (SCPC). Here both earth stations are assigned a narrowband channel onboard the satellite during the length of the call from a limited pool of channels, and is known as SCPC-DAMA. After the communication session is over, both earth stations release their channels, which are then free to be assigned to a new pair of earth stations when requested.

Traffic theory, through the Erlang B formula, helps define the correct number of available voice channels for a pre-determined network size and grade of service, as will be explained shortly. SCPC-DAMA has been the multiple access technique of choice in satellite rural telephony applications since long ago due to its ease of implementation and efficient use of the satellite channel [Ros81]. Demand Assignment TDMA (DA-TDMA) is a demand protocol used to request a time slot on a TDMA network, but its implementation is more complex than SCPC-DAMA, and it is not widely used on telephony applications. TDMA generally requires higher power earth station transmitters than SCPC-FDMA, and is consequently less popular.

Up until this part it has been assumed that all earth stations would have a single user channel per link, but multiplexing technology allows that channel to be shared even further, through the use of Frequency (FDM) and Time (TDM) Division Multiplexing. Since most applications now are digital, TDM is the multiplexing technique of choice. Available technology allows multiplexing of up to 8 and 10 TDM user channels into a single 64 kbps carrier, which is a typical narrowband satellite channel [Alb96]. This technique of multiplexing several users into a single satellite channel is called Multiple Channels per Carrier (MCPC), and it is believed that it would improve not only the capacity but also the revenue of an earth station [Com99]. This assumption will be analyzed later on this work.

2.4.2.2 Topology evaluation techniques

An assumption so far has been that any earth station can communicate with each other at will if the users are more interested in talking to each other on a local loop than in accessing a larger area network, such as the PSTN. In the case of satellite rural telephony it is assumed that the users would like to connect to the PSTN more often than to each other, changing the network topology from full mesh to star, shown in Figures 2.6 and 2.7. A star topology allows all remote nodes to interconnect to the PSTN through a single network element knows as *gateway* or *hub*.

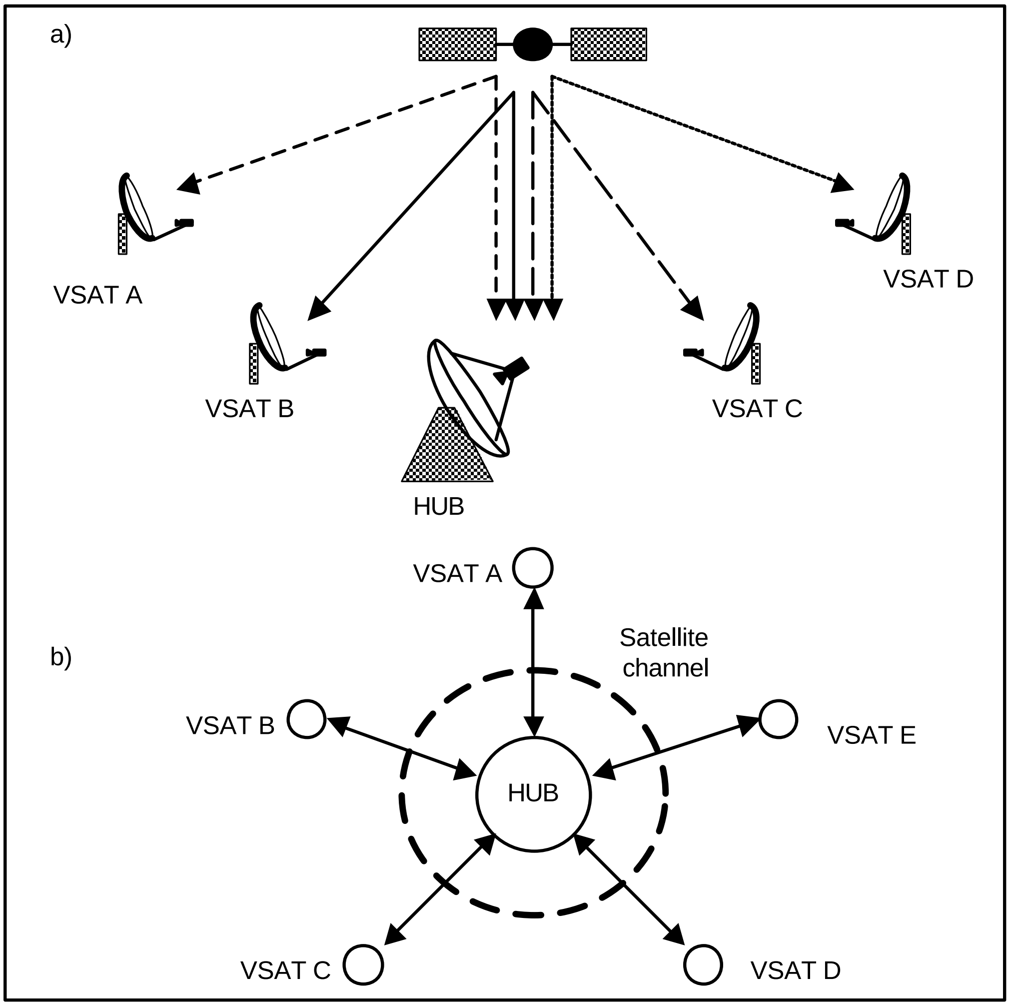


Figure 2.6 Star topology on satellite networks, a) four VSAT example, b) representation.

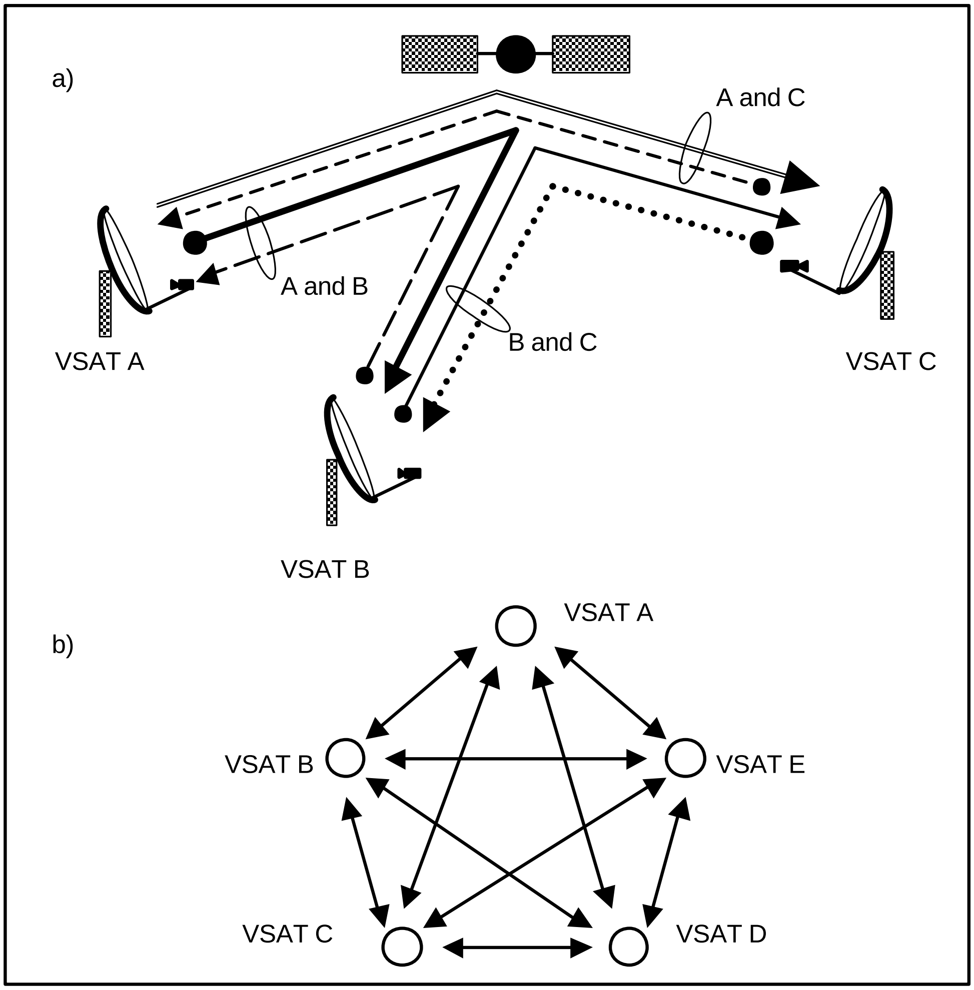


Figure 2.7 Mesh topology on satellite networks, a) 3 VSAT example, b) representation [Mar95]

Several problems have been associated with the star topology, the most important due to its reliability on a single node, the hub, which could prove catastrophic to the whole network if the hub goes down. Another, more important to the customers, is that the hub is usually located at a large city in order to provide quick access to the PSTN, and whose geographical location is transparent to the satellite. As seen from Figure 2.6, a centralized network element (Hub) concentrates all communications. A link between any two VSAT terminals requires two hops, increasing end-to-end delay. A call from a remote user to a subscriber in the large city would include only the satellite cost plus that of a local call, but a call to any other city would increase the cost of the call according to the distance between the hub and the distant subscriber. Thus, a single point of access to the PSTN would imply that any call to other cities apart from the one where the hub is located would increase the cost of the call.

One solution to the single point of access problem for satellite rural telephony has been the use of a partial mesh topology, where a few of the remote earth stations are allowed to perform as gateways to the PSTN in order to reduce long distance fees. Here, the satellite network would find the shortest path and place the call through that specific gateway, decreasing the cost of the call. One problem with this architecture is that the gateway earth stations are larger, more complex and expensive than the usual remote terminals and the network requires a better Network Management System (NMS), which is the software that operates the network.

Several VSAT manufacturing companies currently offer products which can be used on either star or mesh topologies, depending upon the customer's preferences. The question about which topology, mesh or star, is more adequate according to [Mar95] depends upon three factors:

1. The structure of information flow within the network.
2. The requested link quality and capacity.
3. The allowed transmission time delay.

All three factors depend upon their different sensitivities to a single- or double-hop in matters of directionality (one way/two way links), degradation (C/N for single/double hop) or time delay (one/two hops in one/two ways). It is important to mention that double hops in star topology networks happen only in remote to remote communications. Remote to hub are always single hop links. Mesh and star are the most widely used topologies on satellite networks, but that choice must be carefully made based upon the network size, multiple access and traffic requirements. Figures 2.6 and 2.7 show simplified diagrams and topologies of star and mesh satellite networks, allowing bi-directional communications between any VSAT terminal.

The choice of a certain topology has a direct impact upon the earth station's figures of merit: Effective Isotropic Radiated Power (EIRP) and antenna Gain to noise Temperature (G/T). Figure 2.8 shows the behavior of an earth station's requirements for EIRP and G/T for a constant Bit Error Rate (BER) with varying bit rate R_b. It can be seen that the star topology allows for more capacity based on the VSAT's EIRP and G/T figures.

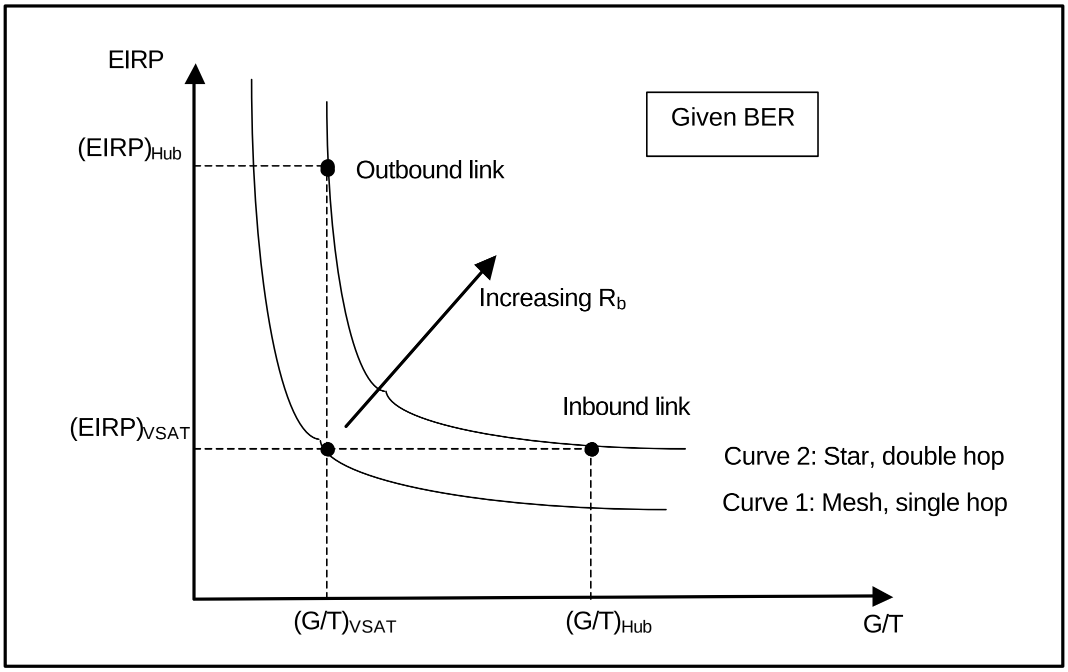


Figure 2.8. EIRP vs. G/T comparison in a VSAT network, VSAT-to-VSAT, from [Mar95].

This larger capacity is due to the presence of the Hub's larger EIRP and G/T figures, which have a positive effect upon the overall link budget, obtaining more capacity with the penalty of a longer delay (two hops). Table 2.3 summarizes the effects of network topology on VSAT capacity and delay.

Table 2.3. Characteristics of star and mesh network configuration, from [Mar95].

Network configuration	Star network (double-hop)	Mesh network (single-hop)
Capacity (given VSAT EIRP and G/T)	large	Small
Delay (from VSAT to VSAT)	0.5 s	0.25 s

2.4.3 Traffic Intensity and Grade of Service

Traffic intensity T is the parameter mentioned at the beginning of this dissertation as one of the most important parameters of rural telephony system design, and its dimensioning is crucial for both the technical design (satellite capacity) and the economic design (business case).

The traffic figure will define the number of minutes per year that each earth station will be operating, which multiplied by the number of earth stations in the network will determine the total yearly revenue. A common way to measure the expected traffic on a telephone network has traditionally been by assigning a certain number of calls per unit time with a certain length of the call. The traffic intensity T expressed in Erlangs is

$$T = \frac{1}{60}\int_0^y x(y)dy = \frac{x \times y}{60} \tag{2.5}$$

where x is the number of calls per hour and y is the mean duration of the call in minutes.

The length of the call usually follows an exponential behavior; a longer call is less likely to happen. Traffic requests are described by a Poisson distribution, which implies exponentially distributed call interarrival times. That provides a metric commonly used to dimension traffic in telephone networks through the use of a statistical formula, the *Erlang B* formula [Mar95], [Rapp96], expressed as

$$\Pr(b) = \frac{\dfrac{A^C}{C!}}{\displaystyle\sum_{k=0}^{C} \frac{A^k}{k!}} = GoS \tag{2.6}$$

where $Pr(b)$ is the blocking probability, A is the traffic intensity per channel in Erlangs and C is the number of available channels.

When using a demand assignment system, a number of available channels C must exist in order to provide a certain *Grade of Service (GoS)* to the user. GoS indicates the probability that a new request for a channel will be blocked due to all channels being busy at the peak traffic hour of the day. Telephone networks generally allow from 0.5 to 5 % blocking probability, or Grade of Service, but usually aim for a 1% GoS, that is, one blocked call every 100 attempts at peak time.

A low GoS increases the number of available channels, thus providing a better service to the user but also increasing overall network cost. On the other hand, a high GoS reduces the number of available channels and overall network cost, which is good for the service provider but at the expense of service quality to the user. A balance is usually found by compromising service quality and overall network cost, with a low GoS at a reasonable network cost.

Freeman [Fre96] mentions that a Grade of Service of 0.01 (1%) is a typical value for most Public Switched Telephone Networks (PSTN). That value is acceptable in a typical wired local area loop since the channel cost is rather low, but in satellite networks the transponder channels are more expensive. A GoS of 1% to 2% is considered good quality on satellite applications, meaning that one call between 50 and 100 will be blocked or lost during the busy hour.

In a congested system the traffic flow lost is related to the GoS by

$$\textit{traffic lost} = \textit{traffic requested} \times Pr(b) \tag{2.7}$$

where $Pr(b)$ is the probability of blocking a call, and the actual traffic flow is

$$\begin{aligned}\textit{traffic flow} &= \textit{traffic requested} - \textit{traffic lost} \\ &= \textit{traffic requested} \times [1-Pr(b)]\end{aligned} \tag{2.8}$$

Satellite networks use the same traffic and blocking probability analysis to define the number of satellite carriers needed to provide thin-route telephone service on demand to multiple earth stations. One difference between wired telephone local loops and radio and satellite networks is that the radio network topology and multiple access exerts a strong influence in the traffic analysis parameters, with an important impact in overall network cost.

Fixed multiple access networks (FDMA, Fixed-SCPC, TDMA) do not need traffic analysis since each earth station has been assigned a permanent individual frequency or time slot, and contention assignment uses a different analysis to define its capacity. Throughout this work, the usage of the variables shown in Equation 2.6 will be n for the number of satellite channels (equivalent to C on Equation 2.6) and T for the traffic intensity in Erlangs (A on Equation 2.6).

On SCPC-DAMA satellite networks the expected long distance traffic T, along with the Erlang B formula helps define the number of n transponder channels to assign to a certain size network with N total nodes. This assumes that $N > n$, according to the pre-defined GoS.

Although both terms sound similar, Grade of Service (GoS) and Quality of Service (QoS) are not the same. GoS is the blocking probability of a call during peak time, a quantifiable and measurable parameter that helps indicate the quality of the network. On the other hand, Quality of Service (QoS) is a rather intangible concept, which really means how happy (or unhappy) a subscriber is with his or her service [Fre96]. A number of parameters can help to better describe the QoS concept. Chapter 4 will further explain the implications of Quality of Service in digital telephony over satellite in both circuit-switched and packet-switched networks.

Chapter 3

Quality of Service in Digital Telephony over Satellite

Telephony is the technology that allows two people to communicate verbally from a distance through the use of electric signals. Voice transmission can take place either in analog or in digital form, depending mainly upon the technology used at the local PSTN Central Office (CO) when switching calls.

Almost all the existing central offices are now digital, although there may be a few analog systems still operational throughout the world. The large investment in CO equipment is justified only by its use over a long operational lifetime, even if that technology is in danger of being rendered obsolete by new technical developments.

Voice can be converted into electrical signals by means of a transducer, such as a microphone. An analog voice signal is an electrical signal carrying the voice information in the form of changes in amplitude and frequency of an electrical time-variant sinusoid waveform. This signal can be conducted over wired (cabled) or wireless (radio) bandpass channels as long as the information signal is modulated and sent over the channels using a higher frequency carrier signal.

Telephone signals between 300 Hz and 3,400 Hz are carried as analog baseband voice over a two-wire link called the local loop and categorized as a voice channel, from the subscriber site to the CO, in analog form in most current telephone networks. As soon as the voice signal reaches the digital CO it is sampled and converted into a digital bit stream of ones and zeroes according to the information content, becoming coded or digitized voice.

A voice coder (Vocoder) performs the process of digitizing voice for storage or communication purposes, and there are several very efficient algorithms and techniques for digitizing voice. The process of coding voice is also known as Pulse Code Modulation (PCM), which is an erroneous term since modulation never takes places at this stage.

Switching takes place at the CO, and the digitized signal will remain digital throughout its transmission over the channel until it reaches the other end's subscriber loop. In our case of interest, switching takes place at the satellite network gateway and routes voice over a satellite channel. If the voice channel originates from the PSTN the digitization process occurred at the local CO, while a voice signal from a remote site probably was digitized at the telephone set or at the earth station telephone interface.

Coded voice may be transmitted and routed through a network as either a constant binary stream over a dedicated network circuit (circuit-switched network) or in segmented form as small reduced-size packets over a common network channel (packet-switched network). Each type of network (circuit- and packet-switched) has its own characteristic behavior regarding voice transmission and affects voice quality in a different fashion over the network.

3.1 Performance Indicators for Quality of Service (QoS) in Digital Voice Transmission

Communication systems are not only required to convey information from one point to another, since this simple notion is missing the important customer's point of view regarding the quality of the service. Users do not need nor want to know about the specific technical parameters of a service, but they are certainly interested in obtaining a "quality service" for whatever application they are using since they are paying the service provider a usage fee.

This quality, along with the service itself, is what will be marketed to potential users so they become attracted to the new service and the network starts having relevant traffic usage. A low quality network will not generate as much revenue as a high quality network since users will avoid calling on non-important issues and may end up using it only for emergencies or work-related calls. This may not be enough traffic to recover the initial investment and the network may not be profitable, so the perception of quality by the network user is critical.

Since there are many different applications demanded from communications networks, it is important to define the most important quality characteristics of a given application, although at times there may be more than one service or application running over a single network. A typical example of a large network running several applications is the telephone network (PSTN), which must run optimally for voice conversations but also for facsimile machines and low bit-rate data modems.

3.1.1 Quality of Service and Network Performance Metrics

There are a number of important parameters that may be analyzed or measured that help establish a network's QoS and Network Performance, which may sound similar but they are not. Clark [Cla91] defines separately both QoS and NP, establishing that "QoS measurements help a telecommunications service or network provider to gauge customer's perceptions of the service. Network Performance parameters, on the other hand, are direct measurements on the performance of the network, in isolation from customer and terminating equipment effects."

This way it can be seen that the difference, although artificial or subjective, gives QoS a wider field than NP due to the user's perceptions. This difference is also becoming important in places where the government regulating entity (the FCC in the US) requires a certain QoS at the network, but only up to a socket in the user's premises. With this arrangement there can be cases when, even by having an excellent NP a user may rate the QoS of a network as poor due to possible problems at either user's premises. Figure 3.1, taken from [Cla91] shows the difference between both terms.

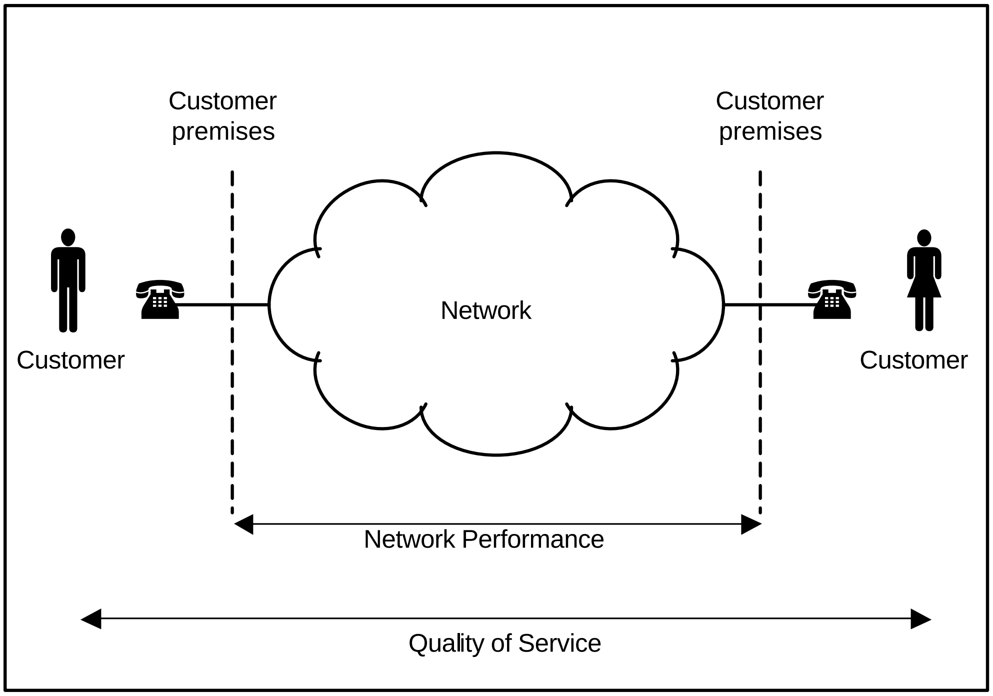


Figure 3.1. Quality of Service and network performance, from [Cla91], p.332.

There are several parameters that help explain the concept of Quality of Service from end to end on a telephone link from a user's point of view, less technical and more on customer satisfaction terms. Rejected calls, which is the number of calls that are blocked due to network congestion during peak times is one of the most common problems that any user can detect on a telephone network. Other factors are intelligibility of speech, interference from other telephone lines, interrupted calls, distortion, and speed of connection setup.

Echo is the reflection of a signal from the other end in long-distance calls where the talker hears his/her own voice slightly delayed. It is very annoying and is especially noticeable on satellite telephone systems. System reliability and quick repair time are crucial since a terminal down will not generate revenue but will generate frustrated customers. Other types of quality metrics are the number of times, the total period of lost or interrupted service time and number of faults per customer line per year. The total time a telephone set (home or payphone) is out of order is also important.

Voice itself has been subjectively measured when testing QoS in telephone networks where a number of people grade the quality of the communications link on a "very-good/ good/ regular/ bad/ very-bad" fashion, and then all grades are averaged, thus obtaining this measure. Although it may not be technically sound, it provides a measure of customer satisfaction, indicating to the engineers whether a problem is present somewhere on the network.

Network performance (NP) can be measured by means of objective testing for certain parameters that help describe the performance of the different systems along the network. Some of the most common parameters to measure are

- Attenuation distortion. This is the variable attenuation of different frequency components of the voice spectrum caused by the line, which attenuates certain frequencies more than others, distorting the tonal balance of the voice.
- Phase distortion or envelope delay. This is the delay of frequency components at the extremes of the voice spectrum due to different propagation velocities in the channel over long distances, due to the channel’s behavior as a bandpass-filter.
- Signal loudness. This is the audio level in the receiver’s phone, which must be at about the same level as the original signal in the transmitter’s phone, in dBm.
- Noise (thermal, impulse, intermodulation and crosstalk) and total signal to noise (S/N) ratio on the telephone line.
- Overall link signal delay.
- Network congestion in direct and alternate routes.

Although both the subjective and objective methods are good measures of the system's quality, it is easier to work with specific parameters and avoid depending upon people's perceptions and shifting moods that may affect grading telephone quality.

3.1.2 Circuit- and Packet-Switched Networks

The Public Switched Telephone Network (PSTN) is the main communications network developed by telephone operating companies and telecommunications service providers to bring communications services to the end user, or subscriber, since the early days of telephony. Also known as the Plain Old Telephone System (POTS), it was initially based on copper wires and cables that ran into every subscriber's home or office to provide basic (analog) telephone service. Central Offices (CO) routed the call to the proper destination as dialed by the calling party.

Local calls were routed through the same CO, and if the call involved a different area, it would use transmission systems between Central Offices for metropolitan, regional or national calls. The way this switching was done defined the type of network: it could be circuit-switched or packet-switched.

In the first type, as mentioned before in this work, one physical link exists between both user lines for the duration of the call and only initial addressing (dialing) is needed. In the second type one physical link is shared among multiple simultaneous users and constant addressing (packet address) is needed.

3.2 Circuit Switched Voice Transmission over Satellite

There are certain aspects of voice transmission over satellite that are specific to circuit switching, which still is the most common way of interconnecting telephone terminals over satellite in the world. Next, a brief introduction to circuit switched telephony and its technical and economic implications when carrying voice over satellite networks.

Although a satellite telephone network would eventually interconnect all calls to the PSTN and switching would take place at the PSTN central office, there is also the possibility of using a switching device at the hub for internal network calls (node to node). In star networks the central node would perform this function while in a mesh network any node could do it. In either case there is no reason to go through the PSTN switches, thus avoiding PSTN access fees.

3.2.1 Circuit Switched Digital Telephony

Ever since the first public telephone systems appeared on the 1860’s circuit switching has been present, although in different forms due to changing technologies. It first appeared in the form of telephone operators who switched lines by connecting copper cables on a switchboard between end users and leaving the line on until one hung up. By the turn of the 20th century large electromechanical switches helped create automatic switch offices, enabling telephone service to be affordable for the public at large [Kes97]. Modern digital switches use arrays of logic gates that close the circuit until one of the users hangs up, releasing the gate to be used by a different user. In most telephone networks the CO still links the calling party's line to the called party's line, thus following a route defined by the Central Office's switch and occupying that connection at all times, so no one else can use it. The user is assigned a full time connection, circuit or channel. According to [Cla91], a circuit-switched exchange must be able at all times to perform the following three actions.

To establish and hold a physical connection between the caller and the calling party for the duration of the call and disconnect it afterwards.

To connect any circuit carrying an incoming call to any other from a multitude of circuits and do this by extracting the correct outgoing circuit from the dialed number.

To prevent new calls intruding into circuits that are already in use, diverting instead the intruder to an alternative circuit that generates a “busy” tone.

A switch transfers information from an input to an output, which can be complicated at some central offices with up to 150,000 inputs and outputs. The two ways to do circuit switching are space division switching and time division switching, briefly described next.

3.2.1.1 Space Division Switches.

A typical space-division switch has a number of inputs arranged in rows and a number of outputs arranged in columns, an arrangement simply called a *crossbar*. To connect any input to any output, the switch controller makes a connection at the point where the input row meets the output column. All other cross points are left unconnected. Figure 3.2 a) shows a crossbar with input B connected to output 5, input C with output 1 and input E with output 3.

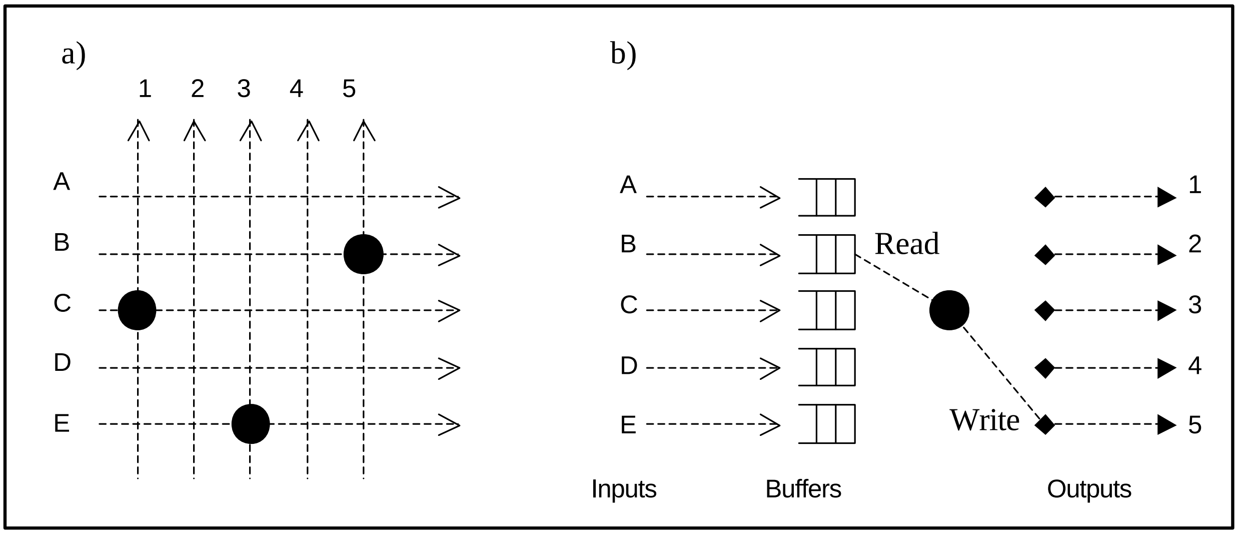


Figure 3.2. Circuit switching. a) Space-division, b) Time-division.

3.2.1.2 Time Division Switches.

A typical time-division switch described by [Kes97] has *n* inputs stored in a temporary buffer. The switch reads from the buffer *n* times faster than the inputs and writes them to the outputs in the proper order. This element is also called a *time-slot interchange*, or *TSI*. For example, to achieve the same connections as in Figure 3.2 a), the time division switch shown in Figure 3.2 b) would first read from B and write to 5, then read from C and write to 2, and finally read from E and write to 2. This type of switch has a very similar principle of operation to a time division multiplexer.

3.2.2 Circuit-Switched Digital Telephone Networks

The Public Switched Telephone Network (PSTN) was designed from the beginning for the analog 4 kHz voice channel, which has provided speech telephony since the 1880's. The only other telecommunications service available at the time was the telegraph, which was developed some 30 years before, and both systems evolved separately until the telegraph lost its place to telex in the 1940's and to the facsimile in the 1960's. Facsimile quickly integrated into the PSTN but it required a modem to be compatible with the analog telephone channel [Fre96].

During the 1950's computer-generated data began to emerge, requiring some type of point-to-point data transmission system, so it fit nicely into the then almost ubiquitous telephone network, although it still needed a modem to integrate the digital service into the analog PSTN. Although digital communication was available by then, it was severely limited by the 4 kHz analog voice channel.

With the development of the transistor and digital communications theory by the late 1940's, applications of digital telephony began to appear in the expansion of the telephone network during the 1960's with Pulse Code Modulation (PCM) transmission and switching systems. PCM was designed to serve speech telephony, and even today more than 80% of the traffic on the PSTN is voice telephony. That is the reason why all digital communication systems today are based around the 64 kbps PCM channel [Fre96]. Although there were some applications with in-band signaling (56 kbps data in the U.S.), today most digital services are based on a clear-channel 64 kbps service.

Telephone companies have been multiplexing long distance calls onto high-speed trunks since early telephone network years, since it is a proven economical advantage. When a large number of telephone calls are going in the same direction, it is possible to carry them as a whole instead of one-by-one, and multiplexing allows that. Since multiplexing equipment must be identical at each end, a number of digital multiplexing hierarchies has been developed around the world [Kes97].

3.2.2.1 Integrated Services Digital Network

Most public telecommunications operators throughout the world have been introducing digital transmission and digital switching into the PSTN, and many of them are at various stages of development of an integrated services digital network (ISDN). This technology allows customers a variety of services, including voice and non-voice, through a digital network that extends to the customer's premises on a limited set of standardized common interfaces.

ISDN provides the user with a basic 64 kbps digital end-to-end connection. This is a big improvement over the analog subscriber lines that still exist in most telephone networks, which require the use of low bit rate modems (≤ 56 kbps) to use digital applications. One advantage of ISDN is that it removes the need for telecommunications customers to have separate physical links to each service network by integrating them in a common 64 kbps channel.

ISDN was designed to provide user interfaces to an existing digital network, working under ITU-T's Signaling System 7 (SS7). Under ISDN a single physical connection is provided to the customer's premises and a range of services are made available from it. Even more beneficial, the services can be used simultaneously because access is not restricted to each individual service in turn. The ISDN basic arrangement is designed to serve, among other services,

- Digital voice.
- 64 kbps data, both circuit- and packet-switched.
- Telex/teletext.
- Facsimile.
- Slow-scan video.

3.2.2.2 ISDN Channel Types

ISDN considers two classes of users, residential and commercial, as well as three types of channels: *B*, *D* and *H*. The *H* channel may also be divided into the *H0* channels and two types of *H1* channels, the *H11* and *H12* channels. There are three types of configurations available to users. One is the Basic Rate Interface (BRI), with information carrying capacity of 144 kbps simultaneously in both directions, and the other two are two different versions of Primary Rate Interfaces (PRI), one with 1,536 kbps and the other with 1,920 kbps capacity simultaneously in both directions. The standard bit rates for user access links are:

- *B*, at 64 kbps for the basic user (bearer) channel.
- *D*, at 16 or 64 kbps for the signaling (demand) channel.
- *H0*, at 384 kbps for the user information channel at the Primary Rate Interfaces (PRI).
- *H11*, at 1,536 kbps for 23 B channels plus 1 D channel (23B + D), totaling 1.544 Mbps.
- *H12*, at 1,920 kbps for 30 B channels plus 1 D channel (30B + D), totaling 2.048 Mbps.

The Basic Rate Interface (BRI) is composed of two *B*-channels and a *D*-channel, referred to as "*2B + D*", with the *D*-channel interface operating at 16 kbps. *H0*-channels may be used separately (384 kbps) or in *H11* (4 *H0* or 3 *H0 + D*) or *H12* (5 *H0 + D*) arrangements.

For the circuit-switching case the *B* channel is fully transparent to the network. It is the *D* channel that carries the circuit-switching control function for its related *B* channels. Whether it is the 16 kbps (BRI) or the 64 kbps (PRI) *D* channel, it is that channel which supports the signaling information from the user's ISDN terminal to the first serving telephone exchange of the telephone company or administration, and then changed into SS7 signaling data. With packet switching two possibilities emerge.

The first basically relies on the *B* channel to carry out OSI layers 1, 2 and 3 functions at separate packet-switching facilities. The *D* channel is used to set up the connection to the local switching exchange at each end of the connection. The second method utilizes the *D* channel exclusively for lower data rate packet packet-switched service where the local interface acts as an ITU-T X-25 data communications device [Fre96].

Since ISDN was designed to operate in an all-digital network, it can operate on those based upon the Open System Interconnection (OSI) layer model. The network's physical layer (layer 1) allows the BRI user-network interface the bi-directional transmission of the two independent *B* channels, which are Time-Division Multiplexed (TDM) over a four-wire interface. Frames are transmitted full duplex, and both point-to-point and point-to-multipoint modes are supported in the BRI.

The Layer 1 supports the PRI only for point-to-point mode. Since the *B* channel is not specified for the data layer (layer 2), the *D* channel controls all of the *B* channels on the interface as well as its own data transmission, including link access, flow control and error detection. The main purpose of the network layer (layer 3) is to establish, maintain and clear network connections such as circuit-switch connections using the B channel; packet switched connections using the *D* or *B* channel; and user-to-user signaling connections using the *D* channel.

3.2.2.3 Broadband ISDN (B-ISDN)

ISDN was designed to operate in an all copper, lower capacity, wired network, at BRI (144 kbps) and PRI (1.544 or 2.048 Mbps), which are referred to as Narrowband ISDN (N-ISDN). However, high bit rate services, such as image and video services cannot be provided in the 64 or 384 kbps channels offered by N-ISDN.

Advances in optical fibers, computing switching and Digital Signal Processing (DSP) have stimulated a rapid demand for higher channel capacities, increasingly replacing copper as a Wide Area Network (WAN) technology, so ISDN is evolving towards what is known as Broadband

ISDN (B-ISDN). A number of technologies can provide these services, more notably ATM, over a number of high digital transport technologies such as the Synchronous Network Hierarchy (SDH) / Synchronous Optical Network (SONET), with standard bit rates for access shown in Table 3.1. B-ISDN and ATM are described in more detail in Appendix A, along with the brief description of a proposed new architecture and protocols which resulted from this research, called Modified ATM over Satellite (MAS) architecture.

Table 3.1. SONET bit rate hierarchy, from [Saa94], p.388.

OC Level	SONET designation	Payload rate (Mbps)	Line Rate (Mbps)
OC-1	STS-1	50.112	51.84
OC-3	STS-3	150.336	155.52
OC-9	STS-9	451.008	466.56
OC-12	STS-12	601.344	622.08
OC-24	STS-24	1202.688	1244.16
OC-48	STS-48	2405.376	2488.32

3.2.3 Satellite Circuit-Switched Network Requirements

Any satellite network can be designed for efficient operation and good commercial quality. However, the most critical problem encountered in the application of satellite telephone networks is interfacing to the terrestrial PSTN. Telephones are nearly the same all over the world but different standards apply in different countries, and when other OSI layers than the physical (satellite channel) are involved (data, network, transport and session), the information is coded and signaling features are included, the possibility for problem grows.

Therefore, interfacing to the PSTN is a potential bottleneck and design challenge, but as Figure 3.3 shows, the importance of satellite communications in thin route applications is also reflected in the many services offered.

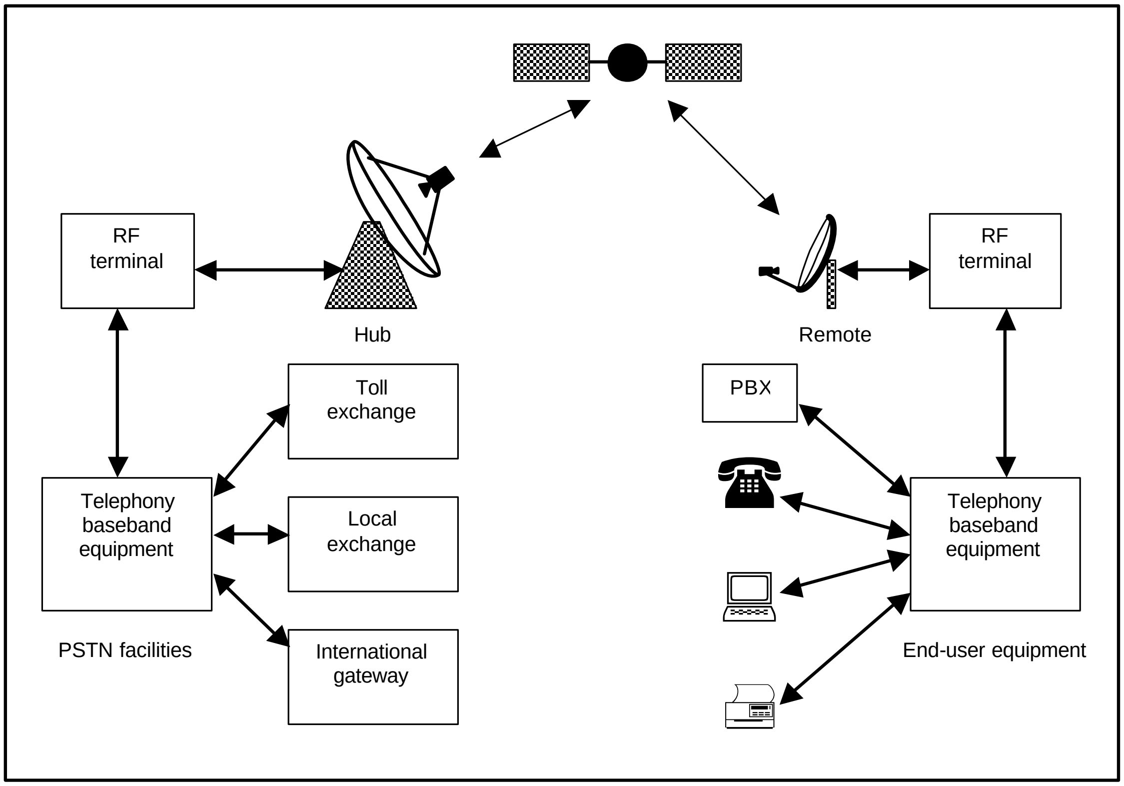


Figure 3.3. Different interfaces on telephone applications, from [Elb97], p.327.

In many cases, such as in rural telephony, the satellite network provides the primary means of communication from a remote location and should be as flexible as the telephone network. The satellite network telephone interface brings with it unique electrical, bandwidth and signaling characteristics that must be compatible with those at the PSTN gateway earth station.

It is common to consider the gateway earth station similar to interconnecting a PBX to the PSTN, though the local exchange interface should be able to access international digital standards like E1, T1/DS1, SS7 and ISDN BRI interfaces, as shown in Table 3.2 from [Elb97].

Table 3.2. Interface standards for satellite telephone connections, from [Elb97], p.328.

Facility	Type of Access	Standard
Private; end-user	Telephone	Two-wire, touch-tone (DTMF)
	PC data	RS-232
	ISDN	Basic Rate (BRI)
	Modem/fax	Same as telephone
	PBX	4-wire E&M, alternatively T1 or E1
PSTN facilities	Local exchange	Two-wire touch-tone (DTMF); 4-wire E&M, T1 or E1
	Toll exchange	Four-wire E&M, T1 or E1
	International gateway	International connection, T1, E1 or SDH

The toll exchange is almost always digital and follows a national standard, besides being usually provided by a major manufacturer and many of them have been recently installed. This may be the easiest part to implement.

The access to an international gateway can occur either at the domestic side or at the international side when interconnecting telephone networks. The domestic side should be interconnected using the same interface as that of the toll exchange, but on the international side the transmission plan and signaling must be clearly specified.

Older PSTN networks tend to use two different types of network signaling, R1 in the Americas and R2 in Europe and the rest of the world, but newer networks are already using SS7, thus rendering it compatible with ISDN. Out-of-band or common channel signaling is standard in a demand assigned SCPC satellite network, as will be discussed later in this work.

3.2.4 Quality of Service in Real-time Voice Applications via Satellite

Voice communications are based on the interaction between two people, and although the common user may not understand technicalities about Quality of Service, a low quality service will immediately be noticed. Satellite communications, especially over Geostationary (GEO) orbit satellites, generate a noticeable delay that is easily recognized, and that has long been known to degrade the quality of voice communications. However, this delay may be acceptable in some cases because it often is the only (or most economic) way to provide telephone service to remote places.

3.2.4.1 Propagation Delay

When transmitting over a GEO satellite channel there is always a propagation time delay, expressed by Equation 3.1, which is the time it takes for the signal to travel from the transmitting station to the satellite

$$t_p = \frac{d}{c} \tag{3.1}$$

where t_p is the propagation time, d is the distance to the satellite in meters and c is the speed of light ($c = 3\times10^8$ m/s). In a typical case with a GEO satellite at an average distance of 38,500 km (38.5×10^6 m) it takes the signal about 0.128 s to reach the satellite and a similar amount of time to return to the receive earth station. This creates a 0.256 s propagation time delay on a one-way call from the transmit earth station to the receive earth station. This delay is important for two-way, real-time applications such as voice or videoconferencing, since it takes more than 0.5 seconds, not counting other minor sources of delay.

3.2.4.2 Echo

One of the most annoying effects on circuit-switched voice transmission over satellite is called "echo", which is caused either by an incorrectly adjusted element (the hybrid) at the remote telephone set, or by audio feeding itself from the handset speaker to the microphone at the remote end. This delay is proportional to the propagation time, and in GEO satellite applications it can be over half a second long, causing an annoying effect to the caller hearing his own words again. Another time-sensitive application is interactive data transaction, especially computer networks, which have a limited time period to acknowledge correct reception of data. This application and its effects over satellite networks will be explained later in this chapter.

Those applications that are time-sensitive must have a guaranteed access to the satellite at all times and show the lowest possible overall delay.

3.3 Packet-switched Telephony over Satellite

Satellite networks are able to meet a wide variety of data communications needs for practically all types of users: business, education, government and individuals. What makes satellite networks attractive is the wide area coverage combined with the ability to provide variable bandwidth with a certain consistency in the quality of the service. A standard 36 MHz transponder can transfer 60 Mbps, suitable for supercomputer applications and multimedia, although most applications do not need such high speeds.

The satellite can carry as much digital information as its transponder bandwidth and/or power limitations allow, and the user may benefit from this as much as its earth station equipment permits it. On the user equipment part, traffic capacity is directly related to the terminal's figures of merit such as antenna size, transmitter power and receiver system noise figure, or EIRP and G/T figures.

Propagation delay on satellite packet links reduces the throughput when there is significant interaction between the two ends of the link, particularly where devices need to exchange control information for flow control, including establishing connections and confirming receipt. The most popular data communications standards are Transmission Control Protocol/Internet Protocol (TCP/IP) and Systems Network Architecture with Synchronous Data Link Control (SNA/SDLC), both of which request retransmission of blocks where errors have been detected.

Although some techniques have been developed to overcome this problem, such as spoofing or using very large window sizes, there is still much work to be done in this area [Had99], [Bem00].

Packetized voice transmission over satellite has been the subject of ongoing research for some time now, but the problems encountered have yet to be solved in a satisfactory fashion. Although there are some satellite networks currently offering some type of packet-voice transmission, the quality of service is still not sufficient to be used widely in a large national telephone network such as the PSTN. Part of the work on this dissertation involved finding an effective way to provide packetized voice over satellite for rural applications.

The preliminary results of a Modified ATM over Satellite (MAS) network architecture for rural telephony involving VSAT networks is presented in Annex A of this document. Although that model is still incomplete, it is a direct result of the research presented in this dissertation.

3.3.1 Introduction to Packet-switched Communications Networks

Most national PSTN systems currently operate over a high-capacity fiber optic backbone, such as SONET, cross-connecting a number of large cities mainly in the broadband and public long distance area. Most large packet networks are still used between PSTN offices since bulk traffic is handled more efficiently this way, but an increasing number of smaller private networks are emerging, mainly to provide Internet connections to clusters of interested users. This usually happens either at a single location (on campus, company facilities) or spread over the city (Internet Service Providers, ISPs).

Although most packet networks are based upon the OSI reference model, none has actually been implemented exactly like that. Many other layer architectures have followed somewhat different but also successful models, such as the one already used in all Internet connections, Transmission Control Protocol/Internet Protocol (TCP/IP), or the more recent ATM protocols.

TCP/IP was initially designed to interconnect and support interworking of dissimilar computers across a network providing end-to-end reliable transport layer functions over IP controlled networks [ATM99]. Voice over IP would rely on the transfer of IP cells over a User Datagram Protocol (UDP) instead of TCP, which is contemplated in the Internet. ATM may be used in a stand-alone ATM network, or may be a medium for carrying IP over it.

The packet networks are designed to efficiently use and share the medium, and the Internet is showing many possibilities and advantages over traditional circuit-switched networks, although it is still under development [Has00].

3.3.2 The Open Systems Interconnection Layered Model

The Open Systems Interconnection (OSI) layer reference model was developed by the International Organization for Standards to provide a basis for defining the interconnection of computer systems. Although the OSI protocols are hardly used by any network, they set the functions of different layers of protocols, which have been followed by most computer network manufacturers and service providers.

For that reason, it is a good idea to understand the OSI seven layer protocol model, shown in Figure 3.4 and explained afterwards in a satellite network environment.

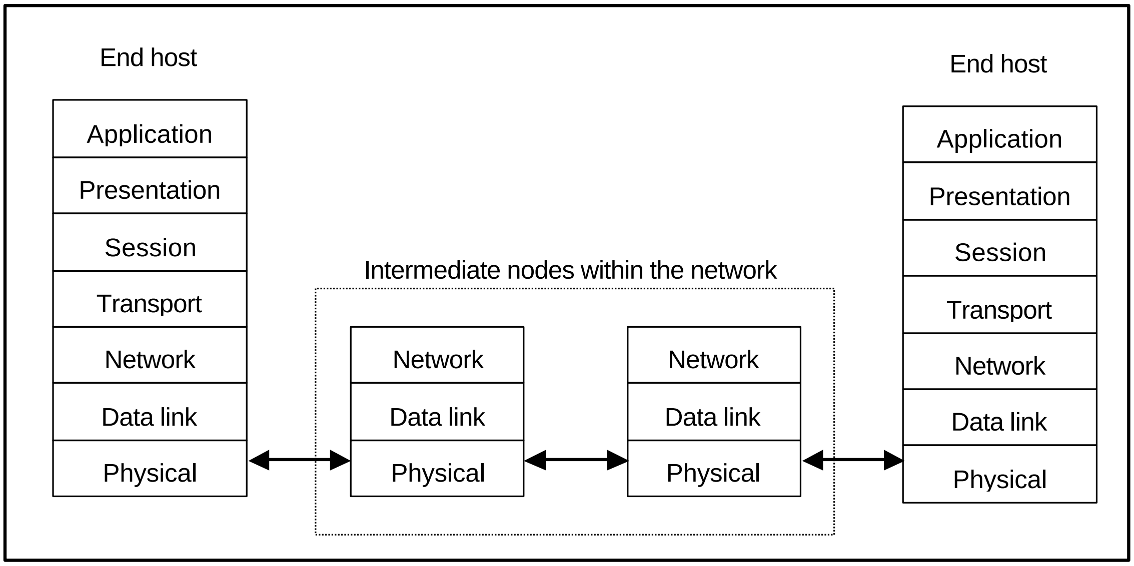


Figure 3.4. The Open Systems Interconnection (OSI) layered model.

Layers in different stacks at the same level are called “peer” layers. At every layer there is a pair of cooperating processes, one on each end host, which exchange messages according to the corresponding layer protocol [Mar95]. The principle of layered protocols is that layers can interact in a peer-to-peer manner with their immediate higher and lower layers, but as long as the interface between the layers is not affected, it is not important how the specific function of a layer is carried out.

Each layer of the OSI model relies upon the service of the layer beneath it, and when receiving a Packet Data Unit (PDU) along with some other parameters from an immediate layer it uses the parameters to include a new header and, possibly, a trailer. This is done so that its peer layer on the other end will know what to do with the packet, a process called "encapsulation", illustrated in Figure 3.5. The shaded areas at the beginning of each segment are the layer's name and the term "Header", e.g. AH stands for Application Header, PH for Presentation Header, etc. The shaded area at the end of the frame on the Data link layer is the "Data link Trailer".

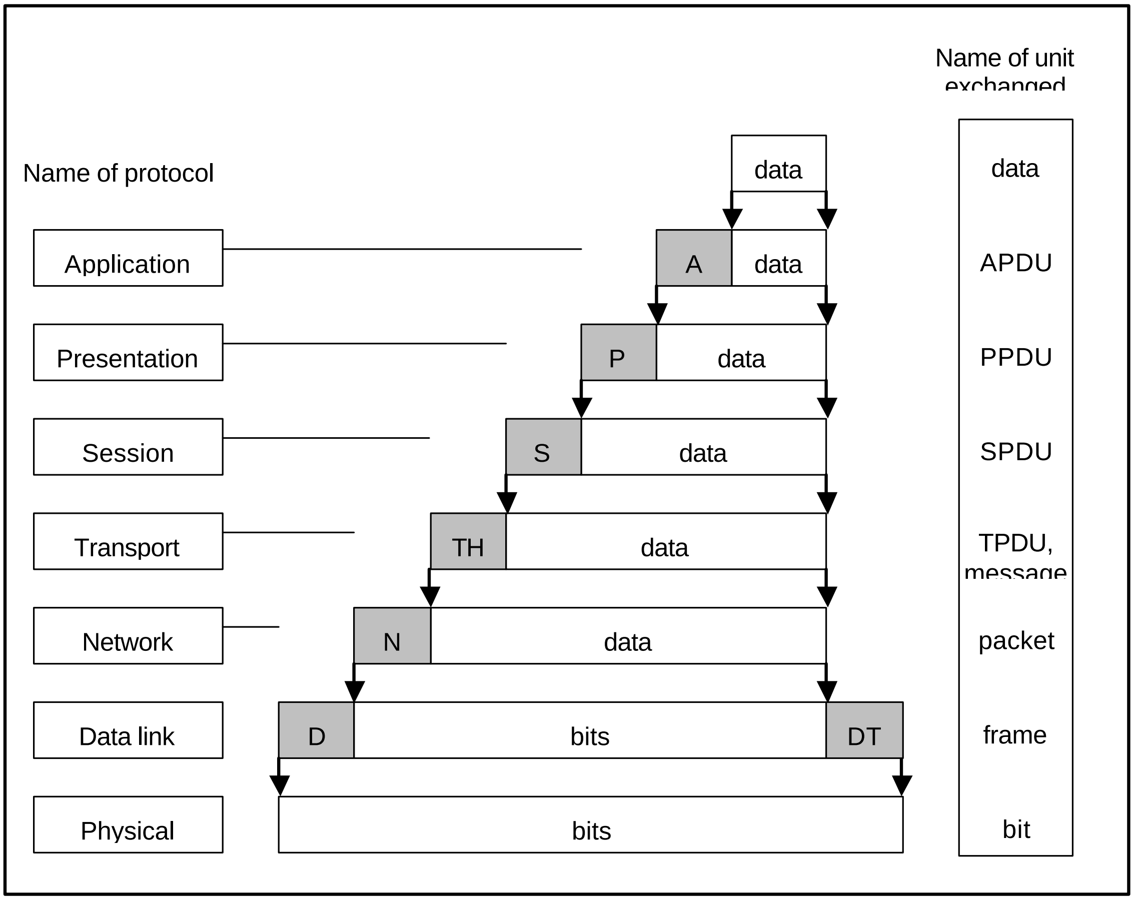


Figure 3.5. Layer to layer encapsulation in the OSI model, from [Mar95], p. 112.

It can be easily seen from Figure 3.5 that a large number of bits in a packet is used only for protocol information (overhead), thus the total information (data) content in a packet depends upon the ratio of useful data bits to the total number of bits. Although this is important, it may lead to misleading conclusions.

In order to increase the useful information (payload) in a packet we can either reduce overhead or increase packet size. The first may increase the possibility of error between layers due to fewer control parameters, while the second may affect the overall latency of the network due to larger packetizing and buffering delays. For more information related to the OSI model, refer to [Saa94], [Dav96], [Fre96] and [Kes97],

3.3.2.1 The Seven OSI Layers

1. The first layer is the *Physical Layer*, which deals with the actual transfer of information between two systems connected over the physical medium, in this case the satellite channel. It provides the physical connectivity between the two systems and may take the form of wired link (cable, wires or optic fibers) or wireless (radio, satellite or infrared/optical). It is concerned with all aspects of bit transmission such as bit format, bit rate, bit error rate, forward error correction (FEC) encoding and decoding, modulation and demodulation, etc. The physical layer is what defines a satellite network from other similar networks, and it includes the radio carrier's (EM wave) magnitude and frequency.
2. The second layer is the *Data link Layer*, which ensures the reliable delivery of data across the physical link by means of performing transmitter and receiver synchronization, flow control and error detection and correction. It sends blocks of data called *frames*, which provide the necessary frame identification to perform the functions described above. In satellite packet networks the data link layer is important since it may be a major cause of delay due to frame errors. In a high latency channel this may generate multiple retransmissions until an acknowledgement (ACK) signal arrives, thus sending the next frame and waiting for the next ACK for a long period of time every frame, slowing down the transmission to an unusable rate and congesting the transmitter. This can be reduced with a number of actions such as *spoofing* (tricking the receiver into believing an ACK has arrived) or by the use of *sliding window* techniques with large windows (transmitting multiple packets before an ACK is received), which require large amounts of buffering capacity.
3. The third layer is the *Network Layer*, which sets up end-to-end connections by routing packets from the source to the destination, determining the individual links to be used and making sure they are available. This implies identifying the destination (addressing), identifying the path (routing), checking resource availability (congestion control) and identifying the link user for billing (accounting). At a satellite network this could happen at the main earth station (hub, gateway) if repeater satellites are used, or onboard the satellite if on-board processing (OBP) satellites with packet-switching capacity are used.

4. The fourth layer is the *Transport Layer*, which is an end-to-end protocol that enables processes on different hosts to communicate by making the network connection that best matches the session requirements in terms of quality of service, data unit size, flow control and error correction needs. If more than one network is available (packet network, circuit-switched data, telephone network, etc.) it chooses between them. It performs functions such as segmenting and reassembling a message, multiplexing several transport connections into a unique network link, and flow control by controlling information flow between end terminals so a fast terminal does not saturate a slow one. Most of these functions in a satellite network would be performed at the hub (multiplexing and flow control) although there would be its counterpart at the remote earth station (segmenting, reassembling).
5. The fifth layer is the *Session Layer*, which provides the means for cooperating presentation entities to organize and synchronize their dialogue and to manage the data exchange. The session protocol implements the services that are required for users of the session layer, negotiates for an appropriate type of session (full duplex or half duplex), and manages the session (synchronizes, interrupts, resumes and releases the connection at the end of the session).
6. The sixth layer is the *Presentation Layer*, which is concerned with data transformation, data formatting and data syntax, which are required to adapt the information-handling characteristics of one application process to those of another application process (use syntax from site A or B). It hides data representation differences between applications to a network standard. It may also encrypt data, both to authenticate it to the receiving application and to prevent unauthorized parties from accessing it.
7. The seventh layer is the *Application Layer*, which provides services to the application processes and serves as a window through which the application gains access to the communication services provided by the model. It also establishes requirements for data syntax and is responsible form overall management of the transaction. The application itself may be executed by a machine (CPU + software) or by a human operator.

3.3.2.2 Applying the OSI Model to Satellite Technology

Only the first four layers (physical, data link, network and transport) are of importance to satellite networks. The upper layers (session, presentation and application) are usually part of the user's end application and thus have very little impact on satellite networks. It is doubtful that a satellite will perform any upper layer function any time soon, although applications are affected by satellite characteristics such as latency.

All repeater satellites operate only at the physical layer, mostly over an analog waveform that contains the physical layer's radio-electric information, which is amplified and shifted in frequency for the downlink. Few satellites currently perform functions above the physical layer, but that seems to be changing since new satellite technology allows some regenerative functions (re-modulation, error detection and correction) on satellites at the data link layer.

Only the most advanced On Board Processing (OBP) satellites perform functions related to the network layer, such as packet switching and routing. That seems to be the direction that future satellites will be taking, at least those designed to provide broadband capacity on global digital networks. References [IEEE97], [IEEE99-1] and [IEEE99-2] mention a wide number of projects working on new architectures, protocols and applications for broadband, packet-satellite networks.

A common term in recent publications refers to the OBP capacity and technology of this type of broadband satellite as "switchboard in the sky" [Bem00], [Far00], [Wit00]. The potential of OBP satellites for networking applications can be easily noted by the over 1,300 expected satellites to operate on Ka-band (30/20 GHz) and V-band (50/40 GHz), with conservative estimates suggesting over 500 broadband satellites by the year 2009, as described by [Had99].

3.3.3 Packet-switched Digital Telephone Networks

Although voice is an analog signal it has been commonly transmitted on digital networks for several decades now with no tangible loss of quality. Satellite voice transmission has been possible due to the use of advanced signal processing algorithms that allow low bit-rate voice compression, eliminating signal redundancy and optimizing bandwidth.

Nevertheless, when voice is packetized its continuous bit stream is segmented into blocks of bits called cells, and with the addition of cell headers they become packets. One problem with packetized voice is that if a packetized payload cell gets corrupted (bit error), little information is lost and the user will hardly notice it, but if a whole packet is lost (header error) or corrupted (burst error) then the QoS will be severely degraded. This makes header errors more important than payload errors. Of the several technologies mentioned to replace the telephone network Voice Telephony over ATM (VTOA) and Voice over IP (VoIP) seem to be the most promising, and there are current efforts to provide both technologies over satellites, so a brief description of each will follow.

3.3.3.1 Voice Telephony over IP (VoIP)

The most common telephone system today is still analog over a wire, and though it is a very old technology it has many advantages: it is simple and keeps end-to-end voice transmission delay very low since electrical signals on cables travel close to the speed of light. On the other hand, noise adds up in the analog signal at all stages of the transmission and there is no way to separate the voice signal from the added noise. Most countries now use digital transmission systems but the subscriber line remains analog, so the voice is converted into a 64 kbps digital data stream and multiplexed in time (TDM) in the first local exchange.

Most telephone conversations only use the channel 40 % of the time, so Voice Activity Detection (VAD) is used on digital voice to transmit only during that time, thus optimizing the channel through the use of statistical multiplexers. If the channel is empty the voice uses it, and if it is busy it waits until it is available. Since this uncertain channel availability is statistical of nature, statistical multiplexers are used, and the variation during the waiting time is called jitter, which needs to be corrected on the receiving side.

The next-generation telephone network will probably use statistical multiplexing and mix voice with data on the same lines. VoIP is mentioned as having a slight advantage over ATM regarding connectivity [Her00] since it does not require setting up virtual channels. VoIP requires the use of the Real Time Protocol (RTP), which allows receivers to compensate for jitter and de-sequencing introduced by IP networks. RTP can be used for any real-time stream of data such as voice and video applications by formatting IP packets carrying isochronous data, including information on the type of data, timestamps and sequence numbers.

RTP does not have any influence on the behavior of the IP network and does not control the service in any way, so RTP packets can be dropped, delayed or de-sequenced just like any other IP packet. RTP is not associated with the Resource reSerVation Protocol (RSVP) since it only allow receivers to recover from network jitter by buffering and sequencing, and provides network information.

RTP is typically used on top the User Datagram Protocol (UDP), which provides notion of port and a checksum. RTP over UDP can reach several destinations, since RTP can be carried by multicast packets. Since each RTP carries a sequence number and timestamp it can manage a reception buffer on the receiver, placing the incoming packet in the corresponding sequence and allocating up to 100 milliseconds of speech before beginning the playback.

If a packet is delayed or lost it can decide to copy the last frame on the packet and play it repeatedly until the timestamp is caught or try to use some interpolation scheme. The packet payload (actual coded speech), specifies the codec type used for voice formatting, which follows the general H.323 standard for the architecture and operation of videoconferencing systems over a packet network. H323 is not specific to IP, since it can also operate over ATM.

The main attractive of VoIP is the possibility of using the Internet to provide telephone service at a fraction of the current cost of calling through the PSTN, independent of the distance and time tariff currently operational. Internet Service providers charge only for the local call plus a standard packet tariff per packet ($/packet) or per data volume ($/Mbyte).

Network convergence is also an attractive option for IP service providers, since it allows the use of a single network for most information transfer needs, along with a larger range of audio quality, from highly compressed voice to high fidelity stereo audio, multicast conferencing and even voice web browsing [Li00].

Internet technology is also relatively immature, with quality and latency still being major issues. Humans can tolerate about 250 ms of latency before it has a noticeable effect, and voice services over the Internet today easily exceed this figure.

3.3.3.2 Improving QoS over IP Telephony

There are two main mechanisms being developed in order to improve the QoS of Voice over IP (VoIP), namely the Integrated Service Model (IntServ), and the Differentiated Services Framework (DiffServ) [Li00].

IntServ must manage resources (bandwidth and buffer) for each real time application. This requires a router to reserve resources using resource reservation protocol (RSVP) in order to provide specific QoS for packet streams, or flows.

The DiffServ architecture can offer each user a range of services differentiated on the basis of performance. Traffic entering a network is classified and conditioned at the boundaries of the network. Users request a specific performance level on a packet-by-packet basis.

Voice over IP would require specific IP hardware such as desktop IP phones and terminals, switches, routers and IP/PSTN gateways, as well as software such as the call manager. IP switches and routers connected to a PBX can carry voice traffic over data IP networks. Long distance calls can be routed through the WAN link and, best of all, the transport for IP telephony would be transparent to the users.

3.3.3.3 ITU Recommendation H.323: Voice over the Internet

The International Telecommunications Union (ITU-T) has been working for a number of years on de creation of a new standard for Voice Telephony over ATM (VoATM), which has been named Recommendation H.323. This recommendation defines procedures for multimedia communications services over packet based networks that do not provide guaranteed QoS. It includes H.323 endpoint elements such as terminals and gateways, where terminals are user devices that provide for real time, two-way multimedia communications with other H.323 endpoints.

Gateways provide for real time, two-way communications between H.323 terminals on packet networks and terminals on N-ISDN, B-ISDN or PSTN. Gatekeepers control access to the packet network at the endpoints and provide other services such as address translation between packet networks and the PSTN. Finally there are the Multipoint Control Units (MCU), which enable three or more terminals or gateways to participate in a conference.

3.3.3.4 Voice Telephony over ATM (VTOA)

A common problem in voice telephony over packet-switched networks is that voice during a conversation is time-sensitive, so the packets must have the lowest possible delay and arrive in orderly sequence at the other endpoint. That is why a connection-oriented (one single route) packet-switched network such as Asynchronous Transfer Mode (ATM) offers many advantages for this type of application.

One of the functions offered on ATM by the equivalent to the OSI Transport Layer called the ATM Application Layer (AAL) is to segment a binary stream into same size cells, with the capacity to create different type services according to its application and time delay requirements.

The ATM Application Layer 1 (AAL 1) provides for Continuous Bit Rate (CBR) service over a Circuit Emulation Service (CES) channel, requiring stringent traffic parameter values on its traffic contract. Although voice can be supported by AAL 5, it is usually carried by AAL 1 for transport over a public ATM network. Until recently ATM only provided voice capabilities at 64 kbps (125 µs/sample), so an AAL 1 voice cell would require 47 bytes (2.94 ms) of waiting time to assemble the packet and then send it. This is called processing delay and it also has an effect on buffering delay.

Much work has been published regarding voice over ATM [Sta95], [Hän98], [Dav99], but only recently are standards emerging, mainly over an AAL 2 Class service platform [Sta99], [McL97-1], [McL97-2] and [Fla97].

3.3.3.5 ITU Recommendations I.363.2, I.366.1 and I.366.2: Voice over ATM

Recently a new subgroup of study emerged, developing new standards called ITU-T Recommendations I.363.2, I.366.1 and I.366.2 that call for the use of the more efficient AAL 2 protocol platform for Variable Bit Rate (VBR) services. This allows the use of compressed voice and video in real time applications over an ATM network, overcoming the excessive bandwidth needed when using Circuit Emulation Service (CES) for Continuous Bit Rate Service (CBR). This standard can only be used when all the network nodes are AAL 2 capable, but it can handle both CBR and VBR traffic, allowing statistical multiplexing, silence detection and suppression and idle channel removal [McL97-1].

ATM provides support for a wide variety of applications and services based upon a different treatment of traffic, which is called Quality of Service (QoS). By performing the proper traffic management, ATM allows networks to achieve network performance objectives that provide the users with its critical QoS performance levels.

Some services demand higher QoS parameters than others do, and ATM guarantees reaching those service requirements based upon the network's performance and capacity. QoS parameters usually include network capacity, latency, bit and packet errors or synchronization problems, and each service has different values for its representative parameters to guarantee its individual QoS over the ATM network.

The Asynchronous Transfer Mode (ATM) standard is based on the evolution of the Integrated Services Digital Network (ISDN), which was designed to "provide subscribers with a single, digital access channel for both voice and data traffic" [Dav99].

ISDN was initially designed as a circuit-switched Time Division Multiplexed (TDM) network but applications soon demanded higher bit rates with the need to provide packet switching capacity, so an improved version of ISDN emerged, called Broadband ISDN (B-ISDN). ATM is a packet-oriented transfer mode that involves switching, multiplexing and transmission of uniform size packets, or groups of data bits, using an asynchronous TDM multiplex technique.

ATM is connection-oriented since every cell in a transmission travels over the same pre-established virtual path. ATM now allows B-ISDN to deliver high bit rate data services to subscribers, and integrates voice, video and data over a single digital network using broadband telecommunications infrastructure.

The possibility to provide capacity and compatibility for future applications makes ATM an attractive technology, which is the main reason this work was based on a modified ATM architecture and protocol, created in order to provide telephone service to rural communities using conventional GEO satellites.

3.4 Quality of Service on Packet-switched Telephony over Satellite

A satellite network must be designed to provide the Quality of Service (QoS) that the application requires in order to function in a satisfactory manner. QoS involves factors such as bit error rate or packet error rate, link availability, throughput, delays or call set-up time. It has been shown that in packet switching networks, QoS applies from end-to-end during the duration of the session, so the design must include provisions over a long call-time.

There are many parameters that can be improved, such as buffer size, number of buffers and other time variant constants depending on the network protocol, and that varies with the application, whether is real-time or non real-time.

ATM has been at the forefront of most broadband satellite networks due to its easy integration into terrestrial networks, although IP-based satellite networks are taking more relevance and will soon clear most of its current real-time problems.

All aspects of IP and ATM over satellite networks are being studied. From introductory articles [Aky97], [Spr98], [Met00], [Far00] to network architectures [Bar95], [Kot97], [Toh98], [Mer99], [Chi99], [Wit00], Quality of Service [Fah95], [Fah96], [Kal96], [Kal98], medium access control [Pey99], traffic management [Goy99], modeling and simulation [Conn99] and to standards [Cue99]. Only the most important concepts are mentioned in this work.

However, it has also been mentioned that in packet transmission over satellite networks, the main problem in providing QoS telephony, resides in both the time delays corresponding to a typical GEO satellite link as well as those found on a typical packet-switched terrestrial network. These delays can take any of two forms: continuous, or variable.

Continuous delays are those associated with processing the voice, switching and routing or propagation. They may be large or short, but they are constant, and thus, can be predicted. On the other hand, variable delays create many problems for the network designer, since an estimate must be made regarding delays, and that estimate will never be exact.

Variable delays involve variations in traffic that create waiting lines at the switches and routers generating jitter and semi-random buffering delay, or errors in bits or packets, requiring retransmissions, thus lowering the network throughput. This section will try to explain briefly each case.

3.4.1 ATM Quality of Service Parameters

An ATM network commits to provide a certain QoS for the end-to-end connection. A number of network performance parameters can be negotiated at the connection setup trough the traffic contract for an efficient service to the traffic descriptors.

CTD (Cell Transfer Delay) is the end-to-end elapsed time of a cell from the moment it exits the source network interface to the corresponding time when it enters the destination network interface.

CDV (Cell Delay Variation) is a component of the cell transfer delay associated with CBR and VBR services, showing the difference in time between the peak CTD minus the fixed CTD.

CLR (Cell Loss Ratio) indicates an acceptable value for loss of cells on a specific network, while still keeping a required QoS during the lifetime of the connection. A lost cell is one that does not arrive within the CTD interval.

CER (Cell Error Ratio) is the ratio of errored cells in a transmission in relation to the total cells sent in as transmission. An errored cell is one with an uncorrectable error at the cell header or a cell with a corrupted cell payload.

SECBR (Severely Errored Cell Block Ratio) is the ratio of cell block with more than 1 bit error in the cell header to the number of successfully delivered cell blocks.

CMR (Cell Misinsertion Rate) indicates the number of received cells at a connection endpoint that were not sent by its other endpoint, thus not intended to arrive at this point, during a period of time.

BT (Burst Tolerance) is an upper bound on the number of cell arrivals observed at the peak rate.

3.4.2 Satellite Packet Network Architectures

Satellite networks are usually defined by their network architecture, protocol layer models and network size and topology. Although generic satellite architectures are usually presented in most references, there must be distinctions regarding their switching standard, in this case IP or ATM over satellite. Satellite ATM (SATM) networks usually require extra information since their Physical Layer parameters are very different from the fiber optic networks that B-ISDN was originally designed to work with.

Satellite IP networks are being designed mainly for Internet applications, thus TCP compatible, which is not friendly for real-time applications such as voice telephony. The terrestrial networks designed to carry packet traffic are mainly based upon fiber-optic technology, with very little deterioration of the signal, no interference, and point to point topologies. The most important networks are SONET, SDH or Fiber Distributed Data Interface (FDDI), capable of carrying Frame Relay Service, mentioned before in Section 3.2.2.3.

Fiber optic networks do not have the long propagation times that satellite links present, so satellites must provide extra attention to this problem and continuing research is being done in this area, as mentioned by [Far00], [Bem00] and [Had99]. New architectures, protocols and interfaces are being developed in order to integrate packet network technology with satellite technology, driven initially by the Internet demand [Abr00] but increasingly by the attractive possibility to offer multimedia and broadband services over large coverage areas. This dissertation includes a novel architecture and protocols to serve telephone and low bit rate services in thin-route application via a Modified ATM Satellite (MAS) network, described in Appendix B of this work.

Most satellite packet network architectures are based on two types of technologies: Bent-pipe satellite networks, and on-board switching satellite networks [Toh98]. There is a big difference between the two, and thus each requires completely different approaches. There are a number of capabilities that both bent-pipe and OBP satellites can perform, with the simplest being the simple relay satellite, growing in complexity up to the several switching functions described later in this chapter.

Figure 3.6 shows the taxonomy of On Board Processing (OBP) capabilities of satellite, adapted from [Toh98].

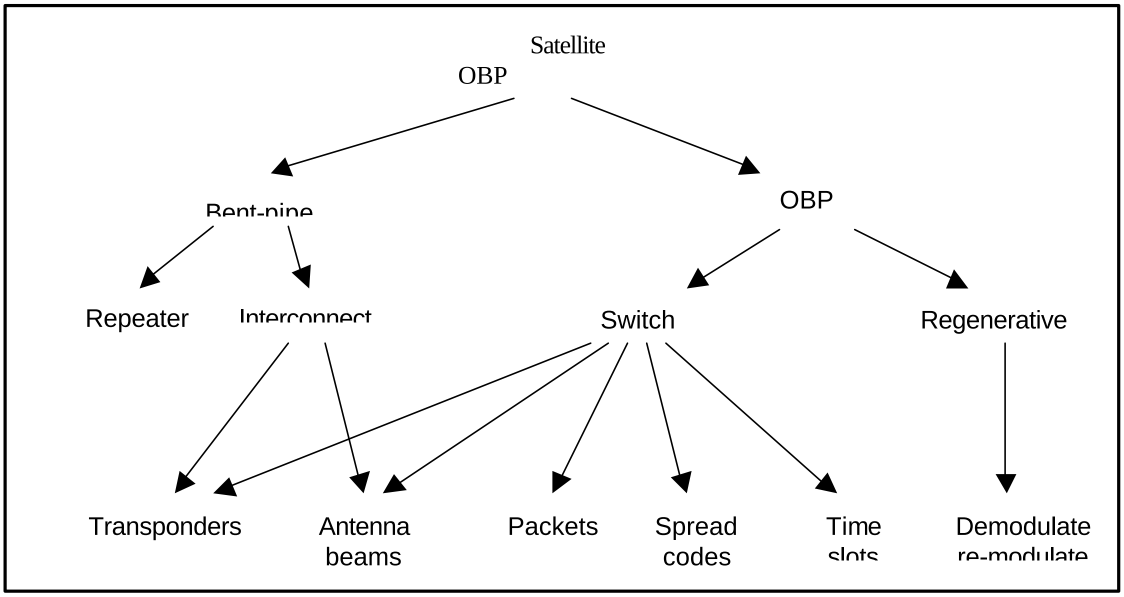


Figure 3.6. Taxonomy for On Board Processing (OBP) satellite architectures, adapted from [Toh00].

3.4.3 Bent-pipe Satellite Network Architecture

Bent-pipe satellite networks use repeater satellites, which only relay packet traffic from one remote user to another through the packet's physical layer. The satellite does not have access to the packet's data link nor transport layers, therefore it cannot switch cells nor route them through virtual paths or channels. This fact makes it easier to use generic (off the shelf) satellites, thus lowering satellite complexity and cost, but requiring instead better performance from the earth stations with an increase on network cost.

The bent-pipe repeater satellite does not need a special Medium Access Control (MAC) layer, except for the basic multiple access technique common in most satellite networks. On the other hand, since the quality of a satellite link depends upon weather conditions, burst errors can severely affect the network's QoS parameters.

A satellite without on-board processing and bit /packet regeneration cannot correct these errors, and the downlink may even increase them. This is a big disadvantage of bent-pipe satellite networks. Figure 3.7 shows the basic architecture of a packet network based on repeater satellite. In this case, even while the satellite is part of the packet network it only performs repeater functions over the physical layer.

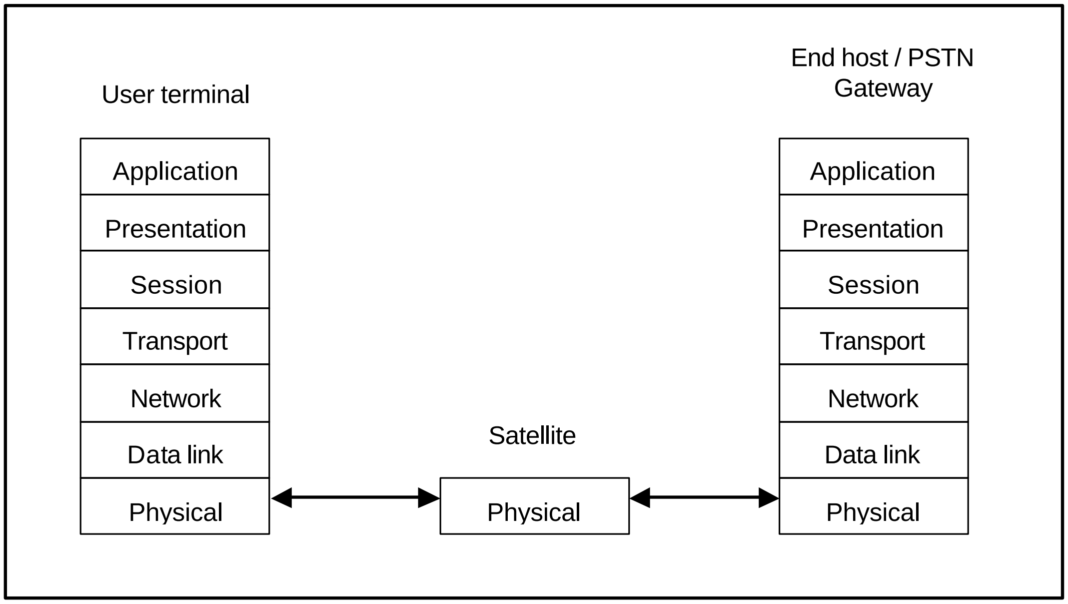


Figure 3.7. Architecture of a bent-pipe (repeater) satellite-based packet network.

3.4.4 On-Board Processing Satellite Network Architecture

On-board processing satellites have the advantage of achieving unrestricted connectivity, lower transmission delay and the possibility to route packets between different earth stations or satellites, if the satellite technology and topology allows to do so.

An on-board processing satellite may have IP or ATM switching capabilities, and thus it can access the packet's data link and network layers, read its virtual path and channel information and forward the packet through its most convenient path according to its internal, on-board routing tables. Instead of output ports in its physical layer, an on-board processing satellite may use different frequencies, codes, antenna beams or time slots.

The on-board processor can also detect and possibly correct bit and packet errors, thus achieving lower bit error rates than bent-pipe satellites. Usually on-board processing satellites have higher operational costs and network complexity, but allow better network operation, management and efficiency.

Figure 3.8 shows the network architecture of an OBP satellite. Here the satellite is now part of the packet network and may perform functions up to the network layer.

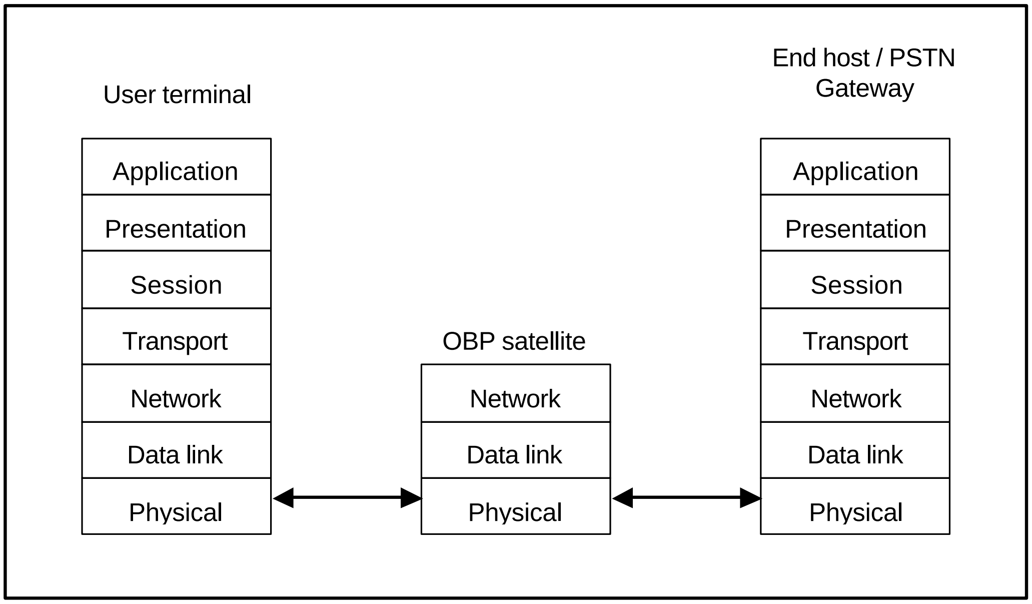


Figure 3.8. On-board switching satellite on satellite networks architecture

Some broadband satellite networks are being design to operate on Low Earth Orbit (LEO) constellations, with numerous satellites moving in different orbital planes. This reduces the propagation delay, having an improvement on overall system latency due to the orbit, and although some of these satellites will be repeater only, there are some networks that have satellites perform onboard switching. As mentioned before, on-board switching improves even more the overall throughput of a satellite network, since the packets can be routed between neighboring satellites until reaching the desired destination.

This type of satellite network performs not only switching but also routing to its user destination using shortest-path routing algorithms. This is not an easy technological task, since the satellites are fast-moving switches with ever-changing ground gateways to many different terrestrial networks, so the satellites must have global routing tables which need to be updated in real-time at all times. It is doubtful anybody has come up with a way to do this yet, so what is currently being done is to upload the routing tables from the gateway under the satellite's path as soon as it appears, and use routing algorithms on the terrestrial nodes. There is much work to be done in this area. Figure 3.9 shows the typical architecture of a broadband satellite-switching network.

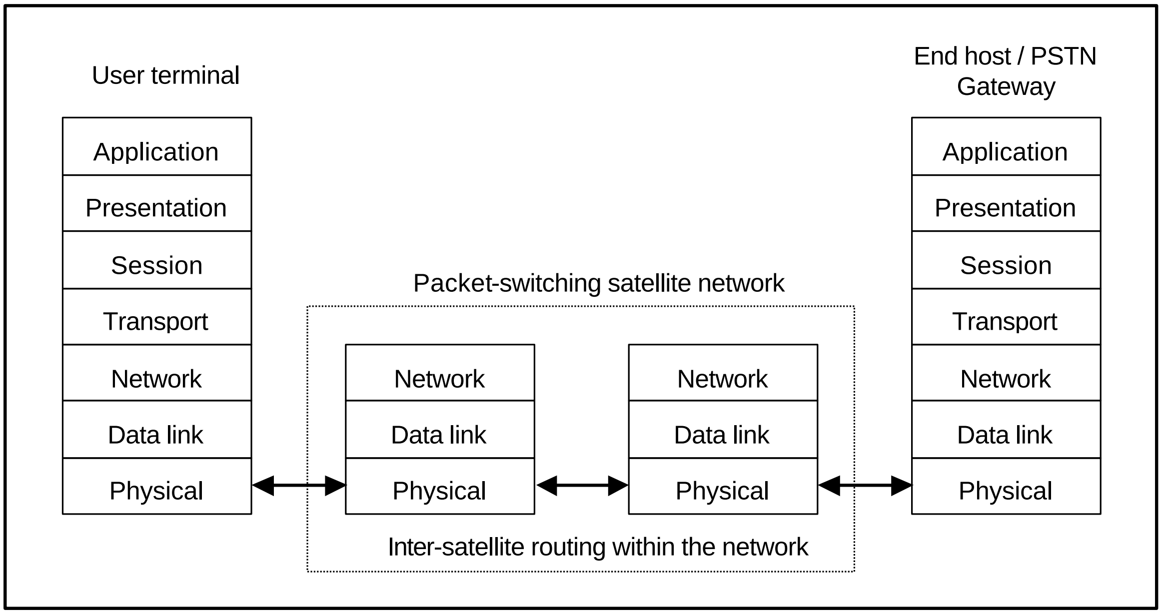


Figure 3.9. Inter-satellite switching architecture on packet-switched satellite networks.

3.4.5 Latency on Satellite Links

Some digital applications may be affected by other delays besides propagation time but still not degrade the quality of the service. Other delays are buffering delay (t_b), transmission (packetizing) delay (t_t) and processing (switching & routing) delay (t_s). These delay times plus propagation delay (t_p) add up to what is called "end to end delay", more commonly known as "latency" (D), described by

$$D = t_t + t_p + t_s + t_b \tag{3.2}$$

Latency is probably the most important source of concern in packet-switched, time-sensitive applications, since it will directly impact the Quality of Service of the network. For digitized and packetized voice undesired effects could affect recognizability (who is speaking), intelligibility (what is being said) and integrity (missing information). In high latency voice links the problem compounds with non-instantaneous conversation, since each caller has to wait a certain amount of time from the moment he stops speaking until the moment he receives a response, even if the other party responded immediately, due to the delays described above. Figure 3.10, shows transmission, processing and buffering delays accounted for by "Tx delay" during transmission at site A, "Rx delay" during reception at site B, and again for the return.

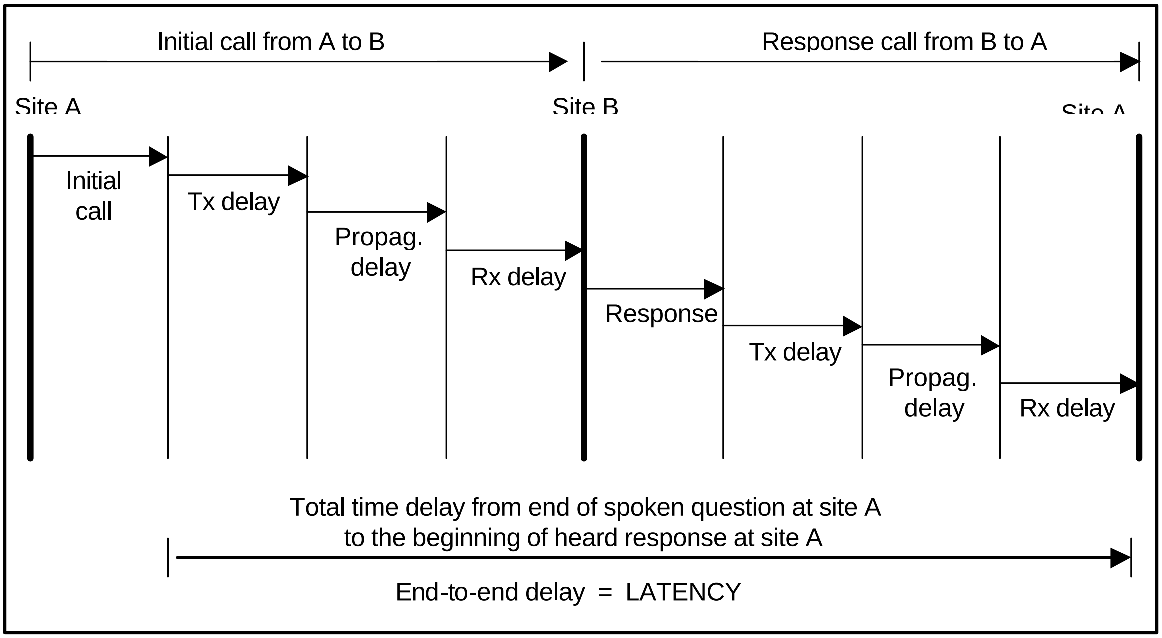


Figure 3.10 End to end delay performance in packet-switched networks.

The traffic performance of a network during cell transmission between connection points defines the Quality of Service (QoS) of the connection. It is defined on an end-to-end basis in terms of several attributes of the end-to-end connection, known as "Traffic Parameters". On the other hand, these parameters can only be guaranteed when the network provides the proper QoS connection through several parameters known as "Network Performance Parameters", described by [Gor95], [Dav96] and [ATM99].

3.5 Packet Satellite System Performance

There are two major challenges in the design of satellite IP and ATM networks. The first is throughput (the number of packets that the network can forward each second) and the second is size (how many remote terminals it can handle simultaneously. Both cases have a common element in terms of available or required bandwidth. For the case of bent-pipe GEO satellites, a maximum bandwidth must be available at all times, independently of its multiple access technique. For that reason the multiple access technique must be carefully chosen. This is well explained in [Mar95], [Elb97], [Kot97], [Had99] and [Eva99] regarding satellite performance. For a more detailed explanation of the following subjects, it is recommended to read [Fre96], [Pet96], [Tan96] or [Kes97].

3.5.1 Bandwidth-Delay Product

In GEO satellite systems propagation delay tends to be the major component of overall delay and a limiting factor of multiple access performance. In satellite links user information is continuously being sent to the channel and the transmitted bit rate defines how many bits are being sent per second. The bandwidth-delay product is a figure of merit that specifies the number of bits inside the channel when transmitting at full capacity. Let tp represent the propagation time between any two earth stations through the satellite in seconds and c the satellite channel capacity in bits per second; then the bandwidth-delay product in bits is

$$d = c\ 5\ \ t_p \tag{3.3}$$

What the bandwidth-delay product will show is how many bits are present inside the channel, which in high latency applications such as GEO satellite links can reach a large quantity of information. This product is very important in high-speed bit data applications, too.

3.5.2 Buffering

If a signal with a 280 ms propagation time carries a 2.048 Mbps signal, the bandwidth-delay product is 573.44 kbits. This means that at any given time there are 573.44 kbits propagating through space in both directions, not present at the transmitting site nor at the receiving site. If any of these bits is affected by impairments or errors, either a retransmission will be needed or Forward Error Correction (FEC) will be attempted. In retransmission all sent information is temporarily stored in memory until no longer needed, a process is known as "buffering". This process takes up much memory, especially for large bandwidth-delay product applications, since all that data must be available for retransmission until the response arrives. Buffer sizing is a critical process in satellite networks, especially for broadband and multimedia applications.

3.5.3 Throughput

Bit errors may occur when some of the traffic arriving at the satellite is affected by propagation impairments (e.g. rain), thus requiring a retransmission of the errored packet or packets. Since the same information has been sent twice but it will be useful only once it takes the place of another packet waiting to be transmitted. The ratio of useful packets (or bits) to the total packets (or bits) sent in a time period is called "throughput".

3.5.4 Congestion control

Congestion is defined as a state in which the network is not able to meet the required QoS for already established connections and/or new connection requests. In order to avoid congestion, traffic control procedures (prevent congestion) and congestion control procedures (minimize intensity and duration of congestion) have been established. Large delays can cause significant increase in the latency of feedback mechanisms for congestion control, with a negative effect in overall QoS.

Chapter 4

Methodology for Cost-effective Network Design

A communications network is a system that interconnects many communication nodes, which are built from generating, storing, processing and transmitting systems (hardware), and many layers of software. The hardware and software in a communications network provide the user with terminal, computational, storage and transmission resources that are used to provide network services. System design is the process of putting together these resources into an efficient and cost-effective whole, which is not easy.

It is important to define the difference between an efficient and an effective communications system. *Efficiency* is concerned with minimizing the cost of producing a given output. *Effectiveness* is concerned with making use of the output to meet the goals of the organization [Lan75]. Figure 4.1 shows how an effective system is a joint concern of both the system's designers and its users, and how an equilibrium must be found between Quality of Service (QoS) and the network's value, and the cost of producing the service. Figure 4.1 a) shows the relationship between QoS vs. Value on one curve and QoS vs. Cost on the other. It can be seen that increasing QoS beyond a certain point does not increase the network's value much, but increases cost rapidly. A satellite system analogy could be reducing the number of blocked calls compared to the cost of adding more RF carriers.

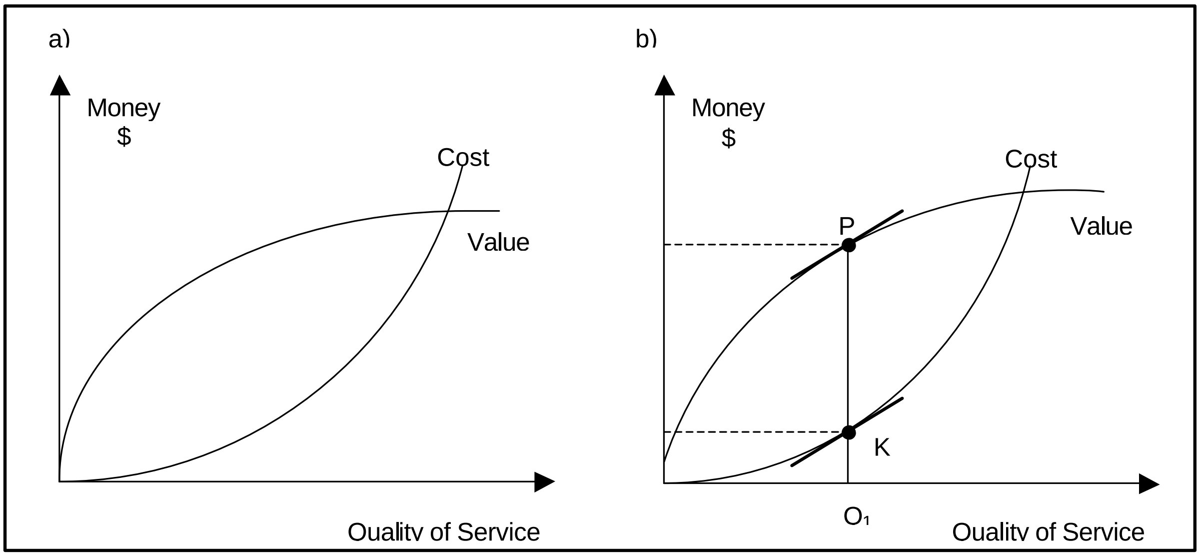


Figure 4.1. Economic impact of Quality of Service in a system, from [Lan75].

As QoS approaches perfection, providing great value, the network's cost rises exponentially, increasing the user cost and lowering requests for service. On the other hand, a low cost network provides the users a low value service, which may generate loss of interest in the service by users. Obviously a middle ground is needed, where an acceptable service value to the user may be obtained with a reasonable investment by the network provider. [Lan75] calls this an *effective system* with an optimum QoS. Figure 4.1 b) shows how the optimum point is found at Q1, the point where the slopes of the tangents at P and K are equal, where the cost of increasing QoS by one unit equals the value to the network of that extra unit of service. This slope change is also referred to as the crossover point between marginal costs and marginal revenue.

A change in technology may offer improvements over a previously considered system so an analysis should be made to find out if a system change or upgrade is justifiable. Figure 4.2 shows how the new system (system 2) provides the same QoS of the previous system, Q1, at the reduced cost L1, so it is an *efficient* system. On the other hand, to achieve an *effective* system (slope at P2 equal to slope at L2) the QoS would be increased to Q2 at a cost of L2. The *effective* system provides a higher QoS than the merely *efficient* system, but at a higher cost. Network designer must determine which case is the best fit to the specific application. This model requires the designer to specify a QoS determined both by the potential value to the users as well as by the cost of providing such quality.

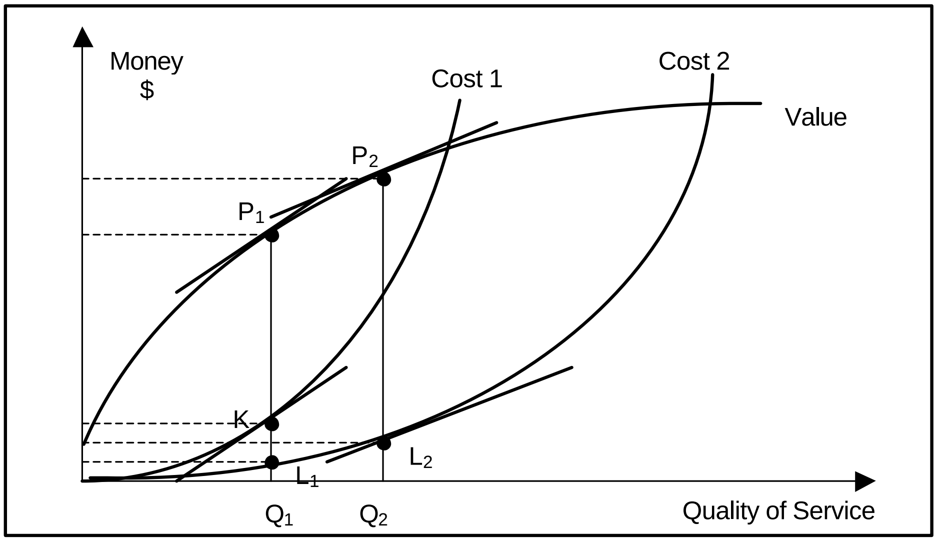


Figure 4.2. Economic impact of Quality of Service on different systems, from [Lan75]

The question now is how to determine the value of the quality of a satellite telephone network, even if the costs can be estimated. Two essential aspects here are the expected net value due to a change in QoS, as well as the expected user behavior. That is where the market study, technical standards, regulatory body requirements and personal experience of the designers and economic planners come into the systems design process.

4.1 Introduction to Communications System Design

In any system some resources are more available than others, and these freely available resources are called *unconstrained resources*, while a resource whose availability determines overall system performance is called a *constrained resource* [Kes97]. In a satellite system the satellite's transponder bandwidth and power constrain the overall performance, as measured by the effective traffic capacity of the link; therefore the satellite is a constrained resource.

A system designer must optimize one or more performance metrics given a set of resource constraints. A *performance metric* measures some aspect of a system's performance, such as traffic capacity, delay, capital cost or user cost. A resource constraint is a limitation on a resource such as bandwidth, transmitter power, maximum network size or user cost that the designer must obey. By explicitly identifying performance metrics and resource constraints, a system designer ensures that the design space is well defined, the solution is feasible and the design is efficient. This allows balancing unconstrained and constrained resources to maximize the design's utility at the lowest cost. A well-designed system maximizes achievable performance while still satisfying the resource constraints.

4.1.1 Problem Definition

Communications systems design is a process that demands a balance between experience and calculated guesses, or as [Kev97] describes it, "... systems design is both an art and a science." Four major reasons make the process hard to control:

1. Intangible parameters that cannot be quantitatively measured, such as simplicity, effectiveness, or even whole concepts such as Quality of Service and user satisfaction.
2. Technology changes can make constraint assumptions obsolete during the system's design, implementation or operational lifetime, forcing the designer to predict tendencies and make a design "future-proof" as much as possible.

3. International standards that may change over time, but often impose difficult or arbitrary constraints that still have to be included in the design.
4. Variable market conditions that may require changes in the design when part of the design is already complete.

Identifying resources and the metrics that can be used in good communication system design is the first step into a methodology that allows cost-efficient network design.

4.1.2 Performance Metrics

System design and network planning requires developing quantitative and qualitative design-to criteria, as mentioned by [Bla98]. The quantitative factors or metrics associated with the system to be designed are called Technical Performance Measures, also called *Performance Metrics*. A description of how to select techniques and metrics for computing and communication system performance can be found in [Jai91] as part of the steps for the Performance Evaluation Study.

4.1.2.1 Traffic Intensity

As mentioned in Section 2.4.3, traffic intensity is an important parameter that helps define the expected number of minutes that each earth station in a satellite communication network will be generating revenue. Therefore, expected traffic intensity is one of the most important performance metrics for the satellite model analysis. This work is based on a rural application where previous telephone service is assumed non-existent, so low traffic figures are used for conservative purposes. Table 4.1 shows the traffic intensity values used in this study for both individual subscribers with a telephone set at home, and a Public Calling Office (PCO), with a public access telephone onsite, from [STM00].

Table 4.1. Expected traffic intensity for satellite rural telephone networks

Traffic amount	Usage time	Traffic Intensity
Very low traffic	1.5 min/hr	0.025 Erlang
Low traffic	3 min/hr	0.05 Erlang
Typical subscriber traffic	6 min/hr	0.10 Erlang
Typical PCO traffic	12 min/hr	0.20 Erlang
High traffic	15 min/hr	0.25 Erlang
Very high traffic	20 min/hr	0.33 Erlang

4.1.2.2 Grade of Service

In any telephone network application the Grade of Service is an important performance metric. GoS is the blocking probability of a call during peak time, a parameter that helps indicate the quality of the network by dimensioning the number of required channels. As mentioned in Section 2.4.3, a GoS of 1% to 2% is considered good quality in satellite applications, meaning that one call in 50 and 100 will be blocked or lost during the busy hour. This allows a good service quality at a reasonable satellite networking cost, since transponder use is expensive. All demand assignment (DAMA) simulations in this work were done assuming a GoS between 1% and 2%.

4.1.2.3 Mean Delay

Mean delay is another common performance metric. The propagation delay in a GEO satellite link is usually around 280 ms one-way due to propagation time. Voice is assumed to have a good QoS if the one way delay is less than 400 ms. This is possible in any circuit-switched, mesh topology network as well as in a VSAT-to-hub satellite link, but not in a VSAT-to-hub-to-VSAT, star topology network.

On the same token, a Voice Telephony over ATM (VTOA), packet-switched transmission may be successful over a GEO satellite link due to its guaranteed virtual channel, depending upon the network topology. Unfortunately, this is not yet the case in Voice over IP (VoIP) transmission over satellite, even when using RSVP or RTP over UDP, as explained in Section 3.3.3.1, due to the lack of guarantees of maximum latency in real-time applications. Therefore, due to the still ongoing research and standards definition of packetized voice over satellite, no packet-switched applications were modeled in this work.

A packet-switched, VTOA application (Modified ATM over Satellite, MAS) model is briefly described in Appendix A, including a proposed network architecture and protocol, a preliminary result from this work.

Therefore, a standard 300 ms mean delay is considered throughout this work due to GEO satellite transmission in circuit-switched applications. No remote-to-remote calls over star topologies are considered in this work, and switching over the PSTN is assumed almost instantaneous. This delay is assumed tolerable by the telephone network's users.

4.1.2.4 Throughput Capacity

Another common performance metric, especially in computer systems and networks is throughput, which is a measure of the efficiency of a transmission in bits per second normalized to channel data rate. In this work, throughput is defined as the capacity of a terminal to transfer information over the satellite channel, which is related to available bandwidth. Two types of satellite transponders are assumed in this work, repeater (bent-pipe) and on-board processing (OBP) transponders. Any transponder has a defined range of the frequency spectrum in which it will carry out its function, which is called transponder bandwidth.

It is assumed that a VSAT terminal uses a 64 kbps signal to transmit from one to eight digital voice signals into a 100 kHz RF channel on a BPSK modulated carrier with 50% roll-off and a small guard band. Most current and proposed Ku- and Ka-band satellites use transponders with 36 or 54 MHz bandwidth, so a full transponder can transmit up to 360 or 540 VSAT carriers with 100 kHz bandwidth in each case if the transponder is not power limited. Some systems mention compressed voice at 8 to 16 kbps transmitted over a 27 kHz channel using BPSK and 50% roll-off, allowing up to 2000 simultaneous channels on a 54 MHz transponder. More compressed voice channels does not seem to be the solution on rural networks, since in either case the terminals cost about the same, thus requiring a huge initial investment in large networks.

Therefore, a variable number of satellite channels in a transponder, with a maximum number of 500 simultaneous satellite channels, is used in this model to simulate a variable sized rural satellite telephone network. All channels are assumed to carry one 64 kbps signal over a 100 kHz carrier from a single terminal at all times, with full control over the carrier while it is assigned to that channel. The 64 kbps signal is a standard digitized voice signal with 8 bits and 8 kHz sampling

4.2 Network Planning Factors

The following sections document the parameters in the network under consideration. The assumptions made about these parameters are intended to restrain the models into realistic and workable limits, allowing reasonable simulation and modeling results.

A network planner operates in a context influenced by a number of factors, described by [Rob99] as technology factors, business factors, organizational factors and environmental factors, each one with a different area of influence. In this work, only the boundaries of some of these factors will be established, since it is an analytical model that is under study rather than the full simulation and measurement of a complete (and specific case) communications network.

4.2.1 System Boundaries

There are several limitations imposed upon the design of rural satellite telephony networks regarding the system model and the required simulations, which may facilitate its analysis and bound its parameters. The network considered in this research consists of an arbitrary number of earth stations networked together via satellite to provide mainly voice and low bit-rate data service to rural locations. Therefore, a number of boundaries have been defined to limit the number of variations to what current technology provides or will soon provide. The core of this work is the methodology followed to optimize network performance. The proposed economic models are a set of equations that allow the analysis of different parameters that influence the network’s topologies, multiple access or multiplexing, looking for cost-effective performance measures.

Satellite telephone networks have numerous parameters and can exist in many different configurations. The following sections will further define the network investigated in this research.

4.2.1.1 Satellite Orbits

The satellite orbit defines the potential service coverage area, which is important, but it also demands a number of requirements from the earth station, which can have an impact on system parameters and cost. It has an impact on QoS (delay, attenuation, BER), on capacity (earth station’s antenna, bandwidth and power) and on cost (earth station’s size, required power and complexity). The sole designation of the satellite’s orbit defines many of the network’s technical and economic advantages and disadvantages, but an orbit must be chosen at some point.

Satellites in Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) help reduce propagation delay and losses but require large constellations of satellites, thus increasing the network’s complexity and overall cost. Geostationary Earth Orbit (GEO) satellites in circular equatorial orbit (inclination angle: 0 degrees) will be used in all the computer analysis of the parametric designs. An average distance of 38,000 km from the satellite to the earth station will be considered, having a clear line of sight from the earth station at a high (>20 degrees) elevation angle. In this dissertation, only GEO satellites will be considered, since they provide available bandwidth capacity and have lower leasing cost per transponder than LEO or MEO satellites.

4.2.1.2 Satellite Link Frequencies

Satellite frequencies are limited to a number of spectrum bands, as agreed by international body standards in order to avoid interference from and with terrestrial systems. The currently allowed bands for Fixed Satellite Service (FSS) in the Americas are shown in Table 4.2, along with other typical satellite parameters. This research will simulate links at Ku band for most applications, and at Ka band for the OBP case.

Table 4.2. Fixed Satellite Service typical satellite parameters

Frequency band	*Satellite EIRP*	*Satellite G/T*	*Transponder Bandwidth*
C-band (6/4 GHz)	36 to 40 dBW	-3 to 2 dB/K	36 MHz
Ku-band (14/11 GHz)	45 to 50 dBW	0 to 5 dB/K	36, 54, 108 MHz
Ka-band (30/20 GHz)	55 to 60 dBW	4 to 9 dB/K	36, 54, 108 MHz
V-band (50/40 GHz)	> 50 dBW	> 5 dB/K	36, 54, 108 MHz

4.2.1.3 Satellite Technology

The satellites considered for simulation and network design in this work have the typical parameters of commercially available GEO satellites, with the following characteristics.

- A generic, readily available satellite able to operate at C, Ku or Ka bands from GEO orbit.
- Enough EIRP to deliver a strong signal over the area of interest as shown in Table 4.2 is assumed at all times in this work.
- Enough G/T ratio to receive good quality signals from small remote earth stations is also assumed in all simulations, as shown in Table 4.2.
- A typical bent-pipe repeater satellite and a regenerative-type on-board processing (OBP) satellite (no packet switching or routing, nor beam or time-slot switching capabilities) are assumed in this work.
- Enough bandwidth and power transponder capacity to serve a large size Wide Area Network (WAN) with multiple sites. Although a larger bandwidth transponder allows higher bit rates and more capacity, there are filter, amplifier linearity, and group delay problems associated

with broadband transmissions. Therefore, a typical 36 MHz transponder will be assumed at all times in this work.

4.2.1.4 Earth Station Technology

There are a number of assumptions for the earth station technologies that fall into the following parameters for all cases throughout the simulations on this work, as mentioned next.

- All earth stations are assumed to be under the satellite's main coverage area, with clear line of sight to the satellite and located at the –3dB edge of the satellite antenna’s main beam.
- All Remote Earth Stations (RES, VSAT terminals) and Gateway Earth Station (GES, Hub) use high gain, directional, parabolic (center-fed, offset or Cassegrain) dish antennas.
- All earth stations include an Outdoor Electronic Unit (ODU) comprising an up/down frequency converter, a Low Noise Amplifier (LNA) or Block-converter (LNB), and a solid state or tube High Power Amplifier (HPA).
- A typical RES should not be larger than 1.8 meters in diameter and HPAs should not have more than 2 Watts of maximum RF output power.
- All earth stations use Indoor Electronic Units (IDU) comprising a generic satellite modem using BPSK, QPSK or any of its variants, and include multiple access control to the satellite.
- All RES include a user interface and terminal equipment (telephone, data port) for an individual user, provide a TDM interface and equipment for multiple users, or access to the PBX or WLL equipment, depending upon each case.
- All IDU equipment is sheltered from the open weather and provided with electric and electromagnetic shielding. All terminal equipment can be controlled and monitored by remote control supervisory operation, and electrical power supplies are assumed available.
- The gateway earth station (GES), or hub, provides direct access to the PSTN at all times through a number of physical connections (circuits or routers), according to the expected channel and traffic capacity analysis.

Typical VSAT prices for a 2-Watt radio and 1.2 m antenna unit, and varying hub sizes for this research are based on the following values, taken from [Mar95], [COM99], [Joh00].

Unit price	10 nodes	50 nodes	100 nodes	500 nodes	>1000 nodes
VSATs	$10,000	$9,000	$7,500	$6,000	$5,000
Hub	$40,000	$100,000	$1,000,000	$1,000,000	$2,500,000

4.2.1.5 Link Availability

A reliable communications link is assumed at all times, with link availability of 99.9% of the time in a year and only 8.77 hr/year of outage time, due mainly to rain. For VSAT networks, quality of service is guaranteed to be a BER (after FEC) better than 10^{-8} for 99.9% of the time (system reliability). The system is assumed to be down 0.1% of the time in a year with a BER higher than 10^{-4}, which may be good for voice transmission but not for data, where a BER lower than 10^{-6} is required. A 99.9 % availability is considered for link budget purposes throughout all simulations in this work. A higher availability figure has a direct impact on important network resources, especially in earth station requirements, forcing an increase in overall costs.

4.2.2 Network Boundaries

Since the models presented in this work are directed towards a general methodology for network design and not to the design of a specific network, the models must allow the designer to “play” with different boundaries, depending upon the desired parameter to optimize.

4.2.2.1 Network Size

If a general methodology for network design is to be used, network size must be a variable parameter. Network size determines the initial cost of the network, so planning for a large or small network should include different boundaries. Depending upon the desired network’s size, topology, multiple access and GoS, the network will require a number of satellite channels for all the network’s nodes. Section 2.4.3 describes how traffic analysis helps in dimensioning the number of channels n required for a certain GoS at a network with N nodes, where $N > n$.

The number of nodes used in this research shows the technical and economic trends when different size networks are used in different cases. A small network requires a different technical and economic analysis than a large network, so variations in size are used throughout the simulations. Different size networks with N nodes and n channels are shown in Table 4.3.

Table 4.3. Number of channels n and number of nodes N for different network sizes

Network Size	Very small	small	regular	medium	large
Fixed assignment *n/N*	20/20	50/50	100/100	200/200	500/500
Demand assignment *n/N* *(GoS)*	10/30 (1.8%)	15/50 (1.2%)	25/100 (1.3%)	50/240 (1.9%)	96/500 (1.8%)

4.2.2.2 Network Quality of Service

As mentioned before, the term "Quality of Service" is a rather intangible concept, with a number of parameters that help to understand it. The parameters used (after Forward Error Correction, FEC) in this work are: BER = 10^{-4} (voice), BER = 10^{-7} (data), Mean delay = 300 ms, GoS between 1% and 2% of blocked calls, 99.9% availability, among other parameters. As mentioned above, these figures give an idea of the Quality of Service of the proposed networks.

4.2.2.3 Network Access to the PSTN / Broadband WANs

The user interface for the rural telephone network is assumed to allow a rural user to call a distant site by means of basic telephone operation, but also to transmit data through the proposed satellite communications system if necessary. The interfacing public switched telephone network (PSTN) uses international communications standards and interfaces, for either basic circuit-switched telephone service as well as the VoIP and VTOA future systems. The Remote Earth Station (RES), or VSAT terminal, has access to common user voice and data interfaces to the IDU equipment. The Gateway Earth Station (GES) is assumed to present a common interface to the PSTN or public IP or ATM networks, along with the proper ATM and Physical layer information. The voice quality must be equal to that expected from the PSTN, even if compressed and digitized. A connection fee to the PSTN is assumed at \$0.04/min per voice channel.

4.2.2.4 User Cost

Since the objective of this research is mainly to provide telephone service to remote locations and villages without it, it is expected that the user cost for the telephone service should remain low. Currently, big long distance companies offer attractive tariffs for urban users around \$0.10 per minute at special times, but these prices can only be offered by multiplexing many calls to nearby destinations, at least during certain routing lines. Economies of scale allow service providers such prices, but only when traffic is high in certain routes, which is not the case in rural telephony. Besides, fiber optic links provide huge capacity that, under high traffic conditions, allows the low prices mentioned above. [Elb97] mentions that the cost per telephone channel of a high-capacity fiber cable is 50% to 90% less expensive than a comparable satellite link, provided that the fiber capacity is fully utilized.

For satellite networks, pricing varies according to the technology used. LEO systems were charging prices for telephone service between $1/min for Globalstar to $3/min for Iridium [Ste96], [Con99], although there is no available service currently offered by either one. VSAT systems show somehow lower prices, ranging between $0.25 to $0.50/min for owned systems and $0.15/min to $0.25/min for leased system [Com99]. Prices are difficult to obtain since few systems are operating anywhere in the world, and pricing information is not easily accessible. Therefore, the $0.20/min to $0.50/min price range will be used throughout the simulations for this research analysis, as mentioned by [Com99] and [Alb93].

4.3 Network Planning Optimization Algorithms

Network planning requires the evaluation of multiple criteria for both economic and technical factors involved in decision making. The different problems in each case may be formulated mathematically, and this formulation mainly consists of two parts.

1) The objective function, which is a mathematical function that shows what the “cost” of a solution would be, cost being any performance related quantity, along with a set of variables describing the possible solution.
2) A set of constraints, expressed as a set of mathematical equations with one or more limitations on the range of acceptable solutions. The constraint equations define the feasible solution region.

An objective function and its associated set of constraints is called a mathematical program, which once formulated allows for an optimal solution that minimizes or maximizes the objective function while satisfying the set of constraints.

This section explains the methodology for using optimization algorithms in communications network planning and design.

4.3.1 Linear Programming

Linear programming is the most widely used form of mathematical programming, that has been developed as a branch of applied mathematics for methodological planning. Linear programming deals with special mathematical methods or algorithms that can be computer programmed to solve specific optimization problems. Sometimes the algorithms produce a globally optimal solution, a local optimal solution or no solution at all, depending upon the algorithm and the problem’s constraints.

Although linear programming has long been used in network planning to optimize telecommunications network design, as mentioned by [Wu84] and [Rob99], telephone and telecommunications companies consider their design algorithms, assumed performance metrics and parameter constraints as sensitive and proprietary information. Therefore it is very difficult to find real cases or examples of network optimization problems, and the authors of papers end up describing only the theory and mathematical tools.

Linear programming is concerned with the problem of optimizing a linear objective function of several variables subject to a set of linear constraints. The canonical form of the problem is described by the two parts previously mentioned in Section 4.3 above.

The first part is the objective function to be maximized (or minimized) described as

$$\max z = c_1 x_1 + c_2 x_2 + c_3 x_3 + \ldots + c_n x_n = \sum_{j=1}^{n} c_j x_j \qquad (4.1)$$

where x_j (j = 1, 2, ..., n) are the decision variables whose optimal value has to be found and c_j (j = 1, 2, ..., n) are the proportional costs that multiply each of the x_j. The term z is the total cost to be maximized (z) or minimized ($-z$) depending upon the specific case.

The second part is the set of constraints, where there are m linear constraint equations for the decision variables, described by

$$a_{11} x_1 + a_{12} x_2 + \cdots + a_{1n} x_n = b_1 \qquad (4.2)$$

$$a_{21} x_1 + a_{22} x_2 + \cdots + a_{2n} x_n = b_2 \qquad (4.3)$$

$$a_{m1} x_1 + a_{m2} x_2 + \cdots + a_{mn} x_n = b_m \qquad (4.4)$$

that can be written as

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} x_j = b_i \, , \quad i = 1, 2, \cdots, m \qquad (4.5)$$

$$x_j = 0, \quad j = 1, 2, \cdots, n \qquad (4.6)$$

Note that both the objective function and the constraint equations are linear functions of x_j, which means that there is also another field for non-linear programming, dealing with the solution of non-linear problems, outside the scope of this work.

When Equations 4.2 to 4.5 result in an inequality (? $a_{ij} x_j$ = or = b_i) they can be converted into an equality by introducing *slack* or *surplus* variables y_m into the equations, representing the excess or difference between both sides of the equation.

The main difficulty for linear programming lies in setting up the model in a clear set of mathematical expressions. Optimization problems most often are stated verbally. The solution procedure is to model the problem with a mathematical program and then solve the program with linear programming techniques. [Bro97] recommends the following approach for transforming a word problem into a mathematical program:

Step 1. Determine the quantity to be optimized and express it as a mathematical function (define input variables).

Step 2. Identify all stipulated requirements, restrictions and limitation, and express them mathematically (define constraints).

Step 3. Express any hidden conditions not explicitly stipulated in the problem but apparent from the physical situation being modeled.

A common optimization problem using linear programming is often stated as

$$\max z = \sum_{j=1}^{n} c_j x_j \text{ given } \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} x_j = b_i \text{ constraints, where } x_j = 0.$$

Each one of the constraint equations can be plotted in a graph defining an individual solution space, so the set of constraints reduces to solving the problem in a feasible solution space, bound by the constraint limits. Solutions can be found graphically and numerically

4.3.2 Break-even Economic Evaluations

Often at the planning stage, early in a project, multiple alternatives with multiple futures are projected. In telecommunication networks this usually means evaluating different traffic conditions for multiple network size scenarios. Each of the financial sources will lend or invest money based on the anticipated sales of the service and will use a varying interest rate based on the anticipated demand for the service.

If the service demand is anticipated to be high the interest rate will be lower than when, anticipated demand, is low; thus the evaluation and presentation of these alternatives is of great importance for the network planner [Bla98].

Break-even analysis is an evaluation technique useful in relating fixed and variable costs to any measured operational activity, and it may be graphical or mathematical in nature. The break-even point is of primary interest since it identifies the range of the decision variable within which the most desirable economic outcome may occur. When the cost of two or more variables is a function of the same variable, it is usually useful to find the value for which the alternatives incur equal cost.

There are mainly two concepts of break-even analysis performed in this dissertation, based mainly on the perception of profits over the network's lifetime with regards to interest rate.

1) The most common type of break-even analysis is performed considering current interest rates from financial entities (e.g. banks), usually between 6 % and 10 % as a yearly interest rate. This way, the break-even point for the return of investment will probably happen somewhere around the half way point of the expected lifetime. This means all capital and operational expenses so far have been recovered and any revenue beyond this point will be a source of profit. This is the most common type of break-even analysis; it is simple and allows a quick view into an investment's future.
2) The second type of break-even analysis is performed considering a very high interest rate, usually between 15 % to 25 % yearly interest rate, and designing for a break-even point at the end of the network's lifetime. This way, by the time the break-even point is reached, the return on investment will have recovered all capital and operational expenses and provided a constant revenue with expected profits already included. This is not a common type of break-even analysis, although it is also simple and guarantees the financial sources a solid return of investment in the future.

The economic models included in this research can present either type of break-even analysis, depending upon the economic risk involved and expected return of investment.

4.3.3 Optimizing Parameters for Minima and Maxima

Optimization is the process of seeking the best value on a decision variable. Since the decision variables are part of a larger mathematical equation, the optimal points can be found by means of calculus-based methods. The slope of a function $y = f(x)$ is defined as the rate of change of the dependant variable y divided by the rate of change of the independent variable x. If a positive change in x results in a positive change in y, the slope is positive. On the other hand, if a positive change in x results in a negative change in y then the slope is negative. If $y = f(x)$ defines a straight line, the rate of change of y with respect to x is the slope of the straight line, so this slope is constant for all points on the straight line, that is, $?y/?x$ = constant.

For a nonlinear function the rate of change of y with respect to changes in x is not constant, but changes with changes in x, so the slope must be evaluated at each point on the curve.

Differential calculus allows successive approximations for the slope at the tangent line of the nonlinear function. In classical optimization, the slope is the instantaneous rate of change that is sought [Bla98], obtained with the first derivative:

$$\left.\frac{df(x)}{dx}\right|_{x=x_o} = 0 \tag{4.7}$$

If the first derivative of $f(x_o)$ equals zero it may imply either an optimum point or a point of inflection at x_o. To be certain about an optimum point it is necessary that the second derivative at x_o be positive or negative: x_o being a minimum if the second derivative is positive and a maximum if the second derivative is negative. If the second derivative is also zero, a higher order derivative is sought until the first nonzero one is found at the *n*th derivative as

$$\left.\frac{d^n f(x)}{dx^n}\right|_{x=x_o} = 0 \tag{4.8}$$

If n is odd, the x_o is a point of inflection. If n is even and if

$$\left.\frac{d^n f(x)}{dx^n}\right|_{x=x_o} < 0 \tag{4.9}$$

then x_o is a local maximum. But if

$$\left.\frac{d^n f(x)}{dx^n}\right|_{x=x_o} > 0 \tag{4.10}$$

then x_o is a local minimum.

4.3.4 Constrained and Unconstrained Optimization

The design of complex systems that are optimum in some sense is an important challenge for the systems engineer, seeking optimum values of design variables. The specific mathematical methods used vary in degree of complexity and depend on the system under study, which may show constrained or unconstrained behavior in some of its parameters.

In a linear program an optimum solution may be determined geometrically by locating the extreme points in a feasible region. In a nonlinear program, even with linear constraints, the optimum solution can occur inside, at the extreme point or on the boundary of a feasible region, and neither case can be considered as an extreme point.

There are several economic decision situations in systems design when two or more cost factors are affected differently by common design variables. Certain parameters may vary directly with an increase in a variable while others may vary inversely. When the total cost of an alternative is a function of increasing and decreasing cost components, a value may exist for the common variable, or variables, which may result in a minimum cost for the alternative. This is called unconstrained optimization theory, and there are several algorithms and optimization methods that help solve this type of problems [Wu84], [Bro97], [Bla98]. That theory is out of the scope of this work.

4.3.5 Evaluation Involving Optimization and Multiple Criteria

Optimization is not an end in itself, it only allows to compare mutually exclusive alternatives into a preferable (optimal) solution, which must lie inside the feasibility region. Usually there is no need to continue improving the design if the dominant criterion is met.

When multiple criteria are present in a decision situation, neither technical nor economic (financial) optimization is enough. Although they are necessary, the optimum design must be extended to include extra information about the degree to which each alternative meets or exceeds the specific criteria.

If possible, a new parameter must be found which allows the previous criteria to be compared against allowing the systems designer to decide which alternative is more convenient for the design. If that is not possible (or very difficult), then a number of subjective ratings may be established for each alternative and compared, and the alternative with the best ratings can be negotiated as the best possible choice. Although not an elegant solution, it can be presented to the decision takers in order to take definitive action.

4.4 Economic Models for Satellite Network Design

This section discusses the typical requirements for the different satellite network economic models, along with the mathematical equations that help define the economic impact of different satellite technologies, network topologies and multiple access techniques in the network's overall economic performance.

4.4.1 Evaluation Techniques

The evaluation of network performance involves a great deal of information analysis. The techniques used in this work allow network planners and designers to evaluate the different technological and economic options that each case provides. A set of analytical models was developed in order to provide both mathematical and graphical performance indicators that allow performance evaluation. Although certain evaluation techniques allow some freedom to interpret the network's technical and economic performance, the final criteria for decision making will depend ultimately on the planner's previous experience, the network's constraints and the financial sources' expected profits analysis. That is to say there are no absolute evaluation technique; each situation is taken independently from others and evaluations are often performed based upon subjective analyses

4.4.2 Satellite Networking Economic Analysis

A satellite network, just like any other business providing communication services, requires a heavy initial investment and a long operational time in order to recover the initial and operational expenses by selling service to its users and subscribers, like any other business. In the specific case of satellite rural telephony, there are a few assumptions that must be made when planning a network since rural users and their economic and demographic environment are not the same as urban users. Some of the assumptions to be considered in this work are explained next.

- *Traffic*. To begin with, if a satellite telephone network needs to be implemented in a rural community, it is safe to assume there is none available there yet, so it is very difficult to come up with a precise estimate of expected traffic. A low expected traffic per terminal is a safe choice, in this case from 3 to 10 call-minutes per hour and only one call per hour ($T=0.05$ to 0.167 Erlang), hoping the demand will increase over the system's lifetime. At this point and for the sake of design feasibility only, an average traffic figure will be applied to all earth stations on the network, and all earth stations will be assumed to generate a uniform distribution of traffic throughout the network's lifetime.
- *Topology*. It may be a good idea to assume that most telephone calls to and from the remote villages will be connected to the PSTN, so a star topology is recommended, accepting that

there will be double hops in calls between remote villages, which seriously affects the quality of service (QoS).

- *Application*. Since the main objective is to provide telecommunications service to remote villages that currently have no service, the problem of what type of services arises during the network planning stage. Once again we can safely assume that voice traffic will be the most required service over data or video transmission or Internet access. The reason is simple: the source for voice communications requires only the user's mouth, which is integrated on all potential users, while data and video services require an extra component, a computer or a camera and monitor. Still, provisions can be made for not just voice, but also general digital access to the remote terminal in case data transmissions need to be sent or received.
- *Symmetry*. In any digital network it is important to define the link traffic symmetry, which means how much information is sent in one direction with respect to the amount of information coming the other way. In data applications such as interactive transactions or Internet access, there is usually a high degree of asymmetry since a small data request generates large amounts of information in return. That is not the case in telephony, where one can safely assume that the amount of information in each direction is equal, thus generating symmetric traffic.

4.4.2.1 Earth Station Segment Costs

The terrestrial segment is probably the most expensive part of a satellite network with a large number of terminals, since it requires a large capital investment plus a maintenance fee over the system's lifetime, which add up to more than half the expenses generated by the network. Both parts of the earth station segment (remote terminals and hub) are expensive, and their unit cost depends directly on the total number of nodes in the network. The larger the network size is, the lower the unit cost for each remote terminal, but then there is a larger cost for the overall network and the hub. On the other hand, the remote earth stations will be generating revenue, so theoretically a large network would not only generate large expenses but also large revenue.

According to their topology, satellite networks can be either centralized (star) or distributed (meshed), which helps define several Quality of Service parameters and also influences the capital and operational costs of the network. All centralized networks require a central (or master) node that controls the network's internal operation, usage, maintenance, billing and access to other networks. It also updates any changes in the network such as adding/deleting new/old nodes, keeps statistics on individual and multiple traffic and keeps track of each node's behavior and operation at all times. A central node must be very reliable since it is a single point of failure and that could be catastrophic for the whole network. This means the central node is usually a complex part of the network; it must include redundant elements and a very complete, large and expensive Network Management System (NMS), a long and complex software program. For those reasons a star satellite network must use an intelligent central node, known as a Master Earth Station (MES) or hub. The cost of a hub is directly proportional to the total network size and multiple access to the satellite, either fixed or by demand, and may cost from $100,000 for 100 nodes to more than $2 Million for more than 2,000 nodes [Mar95]. A hub station usually includes a large parabolic antenna (3.5 m to 10 m) and powerful transmitters (20W to 1 kW) depending upon network size and multiple access, thus the large hub cost. Smaller networks usually lease space on another hub, thus avoiding this expense and only paying an extra fee for the service.

Remote Earth Stations (RES) used on satellite rural telephony act as the remote network nodes and usually involve small terminals, depending upon the system being used. Some Low Earth Orbit (LEO) satellite systems such as the failed Iridium or Globalstar systems required portable handsets or public phone booths with omnidirectional antennas that could be used for rural telephony. These systems were priced between $1,500 and $3,000 for the portable terminal [Joh95]. VSAT systems like those offered by Gilat or HNS used for rural telephony consist of a 0.8 m to 2.4 m parabolic dish antenna, an RF out door unit (ODU) a small in-door unit (IDU) and equipment rack, and their cost varies from $5,000 to $10,000 [Mar95], [Com99]. Early 1980's VISTA Intelsat earth stations for rural telephony used larger 3 to 5 m antennas and were priced at tens of thousands of dollars each.

More complex earth station technology allows the use of better voice coding and compression techniques so more users can be time-multiplexed (TDM) into a single RF channel onboard the satellite. This sounds like an attractive market for medium to large size communities with low traffic, as described by [Alb93], but [Com99] explains how the more complex (and expensive) earth stations only increase the overall network capital cost while providing very little increase in revenue due to the low traffic density. [Com99] further explains how the manufacturing companies have decreased the volume of those products, aiming instead at the more lucrative one- to two-user terminals, where they allege the bulk of the satellite rural telephony market is found.

4.4.2.2 Space Segment Costs

The space segment costs are directly related to the transponder portion required to provide capacity to all earth stations, depending upon the network size, multiple access and topology involved, and are charged either on a monthly or yearly basis. It is a constant source of expense that has not seemed to go down in price over the years, but which will is essential for the service providers to provide telephone service and generate revenue [Mar95], [Joh00]. Transponder cost is directly related to the bandwidth or power requirements from the transponder, both of which are limited, so the satellite operator will charge for the relative transponder power or bandwidth used, whichever has the higher value.

$$Cost_B = \frac{B_{\mathrm{Re}\,q}}{B_{Total}}\left(n \times Cost_{Tp}\right) \tag{4.11}$$

$$Cost_P = \frac{P_{\mathrm{Re}\,q}}{P_{Total}}\left(n \times Cost_{Tp}\right) \tag{4.12}$$

Where n is the number of satellite carriers in the network, B_{Req} and P_{Req} are the earth station's required bandwidth and power from the transponder respectively, and B_{Total} and P_{Total} are the transponder's total bandwidth and power.

Since multiple access protocols allow a more efficient use of the channel resource, in this case the satellite channel, they are directly related to the space segment costs. A fixed demand multiple access network will probably pay more for the space segment than a demand assignment equivalent network, since more capacity will be allocated to it. On the other hand, more satellite capacity could allow more revenue, which is traffic dependent, so again it is the traffic parameter that will help decide which multiple access protocol is more appropriate for a specific network.

FDMA and Fixed-SCPC must pay for the total number of satellite channels assigned to the satellite network, so they are not bandwidth efficient. Since FDMA and SCPC use independent carriers for each channel, a guard band is used to separate adjacent channels and reduce interference among them, thus reducing even more transponder capacity. FDMA and SCPC also require the transponder's power amplifiers to operate into their linear or slightly non-linear region in order to avoid inter-modulation products, which also limits power capacity. It is generally assumed that large networks using FDMA and SCPC render the transponder power-limited rather than bandwidth-limited, so they are charged by the relative power usage.

Demand assignment networks require less satellite capacity since not all network nodes have an assigned channel, so satellite usage costs are lower than fixed demand costs. On the other hand, there are fewer terminals generating revenue so earnings are more limited. One basic reason for which demand assignment is widely used is due to its more efficient use of the channel at all times, provided good traffic analysis was done at the design stage.

4.4.2.3 Networking Costs

Networking costs are those cost associated with interconnecting the new network (in this case the satellite network) to the PSTN. Since the PSTN "sees" the satellite network as a private network, it charges interconnecting fees for each user circuit by unit time, generally per minute. These fees are usually considered low (between $0.03 and $0.05 US) when first learned of, but when added up and multiplied for the number of call minutes per year per number of earth stations, networking costs become a really important part of the overall network operational expenses. Since the user must pay these charges anyway, a low interconnection fee would save them a large amount of money over time, although that is a parameter set up by the PSTN operating company usually under government regulations.

A licensing fee is usually required during the network licensing process from the government regulators in order to process the application. It may be charged as one total fee for the overall network, or as the sum of the individual remote terminal fees plus the hub.

Another type of yearly fee may be required from the satellite operator just to continue renewing the lease, paid at the beginning of the year to guarantee satellite service. It is not related to the actual transponder usage. It may again be a single fee for the whole network, or a single fee per site.

4.4.3 Satellite Networking Economic Models

A typical network evaluation must include all the parameters discussed above, which include costs as well as revenue, so the interested parties (design engineers and economic planners) must work together to present investors a business plan in a clear and detailed way. This should be done following a technical-economic model that takes into consideration all the above issues, specifying the technical and economic parameters of the terrestrial segment, the space segment and the networking segment. The revenue projections must be included in order to compare expenses and revenues and find a break-even point where profits are made at some point in the network's lifetime, while still charging the users a low per-minute-call user tariff.

In order to implement the economic model it is important already to have initial market research results, which will be requested before any large amount of money is committed to the project. Assuming the marketing research is well performed, there will be enough information to determine market segmentation, potential service packages and pricing options required by the different market segments. It is important to understand the market, and its potential use (or lack of use) of the satellite network since this presents a high economic risk.

The satellite communications business may be at risk not only due to wrong traffic analysis, expensive service or bad management, but also to bad Quality of Service, bad network or earth station design, and even sloppy equipment installation or maintenance [Mar95]. If the business plan is inaccurate it may take several years longer (or maybe never!) to reach the breakeven point, which leads to unpleasant situations for both economic planners and engineering designers [Eva99].

Robertazzi defines network planning as "the orderly and efficient deployment and management of communications facilities *over tim*e" [Rob99] different to simple network management. Probably all major economic decisions regarding telecommunication systems planning are based on economic considerations that analyze the economic behavior of the network over its projected lifetime. Some important economic tools to analyze and quantify the changing value of money over time are described in [Sep84] and [Bla98], with an emphasis on communications networks by [Rob99].

These tools allow the analysis of proposed capital investments over time regarding the present value (P), future value (F) and single amount payment series or annuities (A). All these parameters have formulas that help explain the changing value of money at a certain interest rate

(i) over a certain number (t) of interest periods of time. Table 4.4 shows the summary of interest formulas, taken from [Bla98].

Table 4.4. Summary of interest formulas, from [Bla98]

Formula name	*Function*	*Formula*	*Designation*
Single-payment compound formula	Given P, Find F	$F = P(1+i)^t$	$F = P\ (F/P, i, t)$
Single-payment present amount	Given F, Find P	$P = F\left[\frac{1}{(1+i)^t}\right]$	$P = F\ (P/F, i, t)$
Equal-payment present amount	Given A, Find F	$F = A\left[\frac{(1+i)^t - 1}{i}\right]$	$F = A\ (F/A, i, t)$
Equal-payment-series sinking fund	Given F, Find A	$A = F\left[\frac{i}{(1+i)^t - 1}\right]$	$A = F\ (A/F, i, t)$
Equal-payment-series present amount	Given A, Find P	$P = A\left[\frac{(1+i)^t - 1}{i(1+i)^t}\right]$	$P = A\ (P/A, i, t)$
Equal-payment-series capital recovery	Given P, Find A	$A = P\left[\frac{i(1+i)^t}{(1+i)^t - 1}\right]$	$A = P\ (A/P, i, t)$

One of the simplest ways to find the monetary value of an investment over time is to assume initial and expected periodic expenses and revenue over a number of years in the future, and bring back those amounts to present value (P) at a certain interest rate. That way the economic planners and investors can take calculated investment decisions.

Next a typical evaluation model for a star topology, Ku-band, 64 kbps per channel, VSAT network for telephone applications will be presented, as evaluated for Fixed-SCPC multiple access. All models from Sections 4.4.3.1 to 4.4.3.5 follow the same sequence but require the set of equations applicable to each case. Table 4.5 shows the terminology used in this analysis.

Table 4.5. Glossary of economic network analysis terms

VSAT parameters		Hub parameters		Network parameters	
V1	VSAT capital cost	*H1*	Hub capital cost	*N*	No. network nodes
V2	VSAT variable cost	*H2*	Hub variable cost	*n*	No. RF satellite carriers
TV	VSAT total cost	*TH*	Hub total cost	*t*	Time period
CV	VSAT unit cost	*CH*	Hub unit cost	*i*	Interest rate
LV	VSAT lease cost/unit	*LH*	Hub lease cost	*Lt*	Total lifetime period
MV	VSAT maintenance cost	*MH*	Hub maintenance cost	*COT*	Total capital cost
IV	VSAT installation cost	*IH*	Hub installation cost	*RE*	Total lifetime revenue
FV	VSAT licensing fee	*FH*	Hub licensing fee	*PR*	Total lifetime profits
SV	VSAT satellite cost	*SH*	Hub satellite cost	*TS*	Exp. user satellite traffic
AV	VSAT PSTN access fee	*AH*	Hub PSTN access fee	*OT*	Operational time (min/yr)
NV	VSAT networking cost	*NH*	Hub networking cost	*OD*	Operational day (hr/day)
r	TDM user channels	*g*	Mesh gateways or hubs	*CU*	User cost ($/min)

4.4.3.1 Fixed-SCPC

In this model, the Fixed SCPC satellite network follows the distribution of a star topology with all VSATs transmitting on a pre-assigned frequency and accessing the PSTN through a hub earth station, as shown in Figure 4.3.

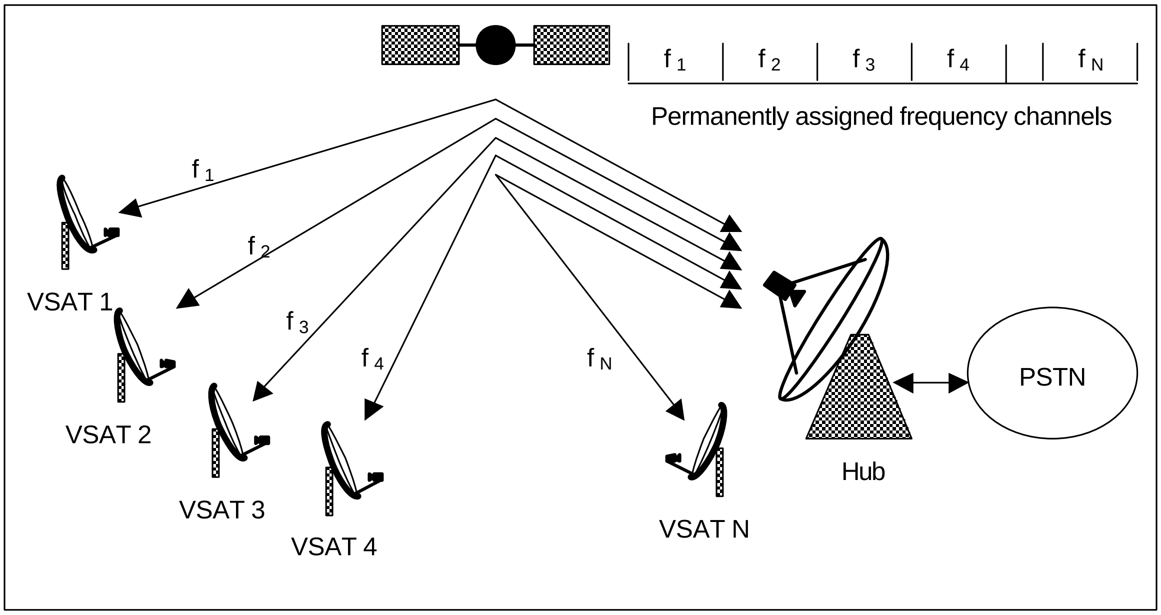


Figure 4.3. Fixed SCPC satellite network to be simulated

Terrestrial Segment Cost, Remote Nodes (VSATs).

The VSAT capital costs $V1$ for a fixed SCPC satellite network at the beginning of its lifetime are described as

$$V1 = N\,(CV + IV + FV) \tag{4.13}$$

The VSATs variable costs $V2$ may be considered as a number of equal payment series present amount (obtained for present value P given A, table 4.4) over a period of time of t years are described by Equation (4.14), where $V2$ is the total amount A, as follows.

$$V2 = A = N\,[LV + MV + SV + (AV \times OT)] \tag{4.14}$$

Since $P = V2(P/A\ ,\ i,\ t)$ according to Table 4.4, we have that the present value of the variable VSAT costs over t years is obtained as

$$P = N\,[LV + MV + SV + (AV \times OT)]\,(P/A, i, t) \tag{4.15}$$

It is easy to see that the single most important component in the cost parameters shown from (4.13) to (4.15) is N, the total number of VSAT network nodes, which controls the cost of all other parameters. That is the reason why it has previously been established as the main contribution to network costs.

The total present value cost for the remote VSAT terminals is the sum of both terms $V1$ and $V2$ over the system's lifetime and is termed TV, expressed by

$$TV = V1 + \sum_{t=1}^{Lt} V2 \tag{4.16}$$

$$TV = N\left(CV + IV + FV\right) + \sum_{T=1}^{Lt} N\left[LV + MV + SV + \left(AV \times OT\right)\right]\left(P\!\!\diagup_{\!A}, i, t\right) \tag{4.17}$$

Terrestrial Segment Cost, Centralized Node (Hub).

The Hub capital costs H1 for the same fixed SCPC satellite network at the beginning of its lifetime are also described as

$$H1 = CH + IH + FH \tag{4.18}$$

while the variable costs H2 (also obtained for present value) over the same period of time of t years are described by

$$H2 = A = LH + MH + SH + (AH \times OT) \tag{4.19}$$

In this specific example, the outbound link from the hub to the VSATs may be configured as an identical number of fixed SCPC channels on board the satellite, or it may take another form, such as Time Division Multiplex (TDM). This would require a different analysis for occupied bandwidth, thus having a different satellite cost. We keep the same fixed SCPC bi-directional arrangement for ease of explanation.

Taking again the Present Value formula from Table 4.4, we have that the hub variable costs over time can be found as

$$P = [LH + MH + SH + (AH \times OT)]\ (P/A, i, t) \tag{4.20}$$

Again, the total present value of cost for the hub is the sum of H1 and H2 as

$$TH = H1 + \sum_{t=1}^{Lt} H2 \tag{4.21}$$

$$TH = CH + IH + FH + \sum_{T=1}^{Lt} \left[LH + MH + SH + (AH \times OT)\right]\left(P/_{A}, i, t\right) \tag{4.22}$$

Networking Costs

The networking costs have already been included in Equations (4.14) and (4.19) as the product of the total network nodes with the PSTN access fee multiplied by the channel's operational time at both the VSAT and hub sites as

$$NV = \sum_{t=1}^{Lt} N(AV \times OT)\left[P/_{A}, i, t\right] \tag{4.23}$$

and

$$NH = \sum_{t=1}^{Lt} N(AH \times OT)\left[P/_{A}, i, t\right] \tag{4.24}$$

terms in each case. Here can be seen again the importance of the network size N, as mentioned before, but there is another term just as important; the AV and AH charge demanded to access the PSTN, or the network access tariff. What these terms show is that the PSTN tariff is as important as the other terms regarding networking costs, and a high or low tariff has a large impact on the overall networking costs. This is often a hidden cost, not obvious at first analysis.

Another potentially large cost may be the long distance cost inside the PSTN. When a remote user calls from the remote VSAT terminal through the satellite link, he or she is only charged the cost of the satellite link and the PSTN access fee, but that is assuming the call will end in the PSTN local area. If the call must be routed to another city or region there will be an extra charge, a PSTN long distance charge, thus increasing the cost of the call. This happens mostly in star topology networks, but it may also be present in mesh networks if the number of PSTN gateways is small. Since this case would require not only a different traffic intensity analysis (long distance into the PSTN) with different, often distance and time related tariffs, it is considered outside the scope of this work.

Revenue Calculation

The calculation of revenue is one of the most important analyses in the planning of a communications network, as in any other business. As mentioned before, revenue is directly dependent upon expected traffic intensity and it may be considered as a series amount of earnings over the network's lifetime. Traffic figures help define the expected amount of usage time that each earth station will serve, which is the time the terminal will also be generating revenue.

Therefore the estimate of network traffic intensity is probably the major assignment in network planning and design, which could make or break hopes in the business plan. Traffic will define the earth station's Operating Time (*OT*), which is the number of minutes in a year that the earth station is expected to be operational.

Nevertheless, a telephone terminal will not be operational 24 hr/day (525,600 min/yr), so a reasonable number of hours should be found when the terminal would be available to the users. For a rural telephone terminal, it would usually be placed at some common access facility and a common usage time could be a typical establishment's working hours, e.g. between 8:00 AM and 10:00 PM, which is 14 hours a day. A typical Available Time (*AT*) for this example would be obtained as

$$AT = (365\text{day/yr}) \times (14\text{ hr/day}) \times (60\text{ min/hr}) = 306{,}000\text{ min/yr.}$$

Now, the Operational Time (*OT*) must be found, that is, how many of those minutes will actually be carrying a conversation, according to traffic intensity $TS = ?/\mu$, where $1/\,?$ is idle time between calls and $1/\mu$ is average holding time. For a traffic of 0.05 Erlang (3 min/hr) *OT* is

$$OT = TS \times AT \tag{4.25}$$

$$OT = (0.05\text{ Erlang}) \times (306{,}600\text{ min/yr}) = 15{,}330\text{ call-minutes/yr}$$

Traffic intensity estimation is a difficult task by itself since it involves evaluating multiple user behaviors for a large network, and coming up with a single (average) figure when every user has a different one. The impact of traffic estimation on revenue is important because it is the single term in the revenue equation that is based solely on statistical assumptions.

Revenue is calculated by obtaining the average OT of each network node (VSAT terminal) and charging the user per-minute-tariff (user cost, CU) to each one of them, and then multiplying that value by the total number of operational nodes as

$$RE = N\,(OT \times CU) \tag{4.26}$$

Again, considering the revenue as a yearly series amount, its present value earnings over the network's entire lifetime can be obtained as

$$RE = \sum_{t=1}^{Lt} N\left(OT \times CU\right)\left[{}^{P}\!/_{A}, i, t\right] \tag{4.27}$$

A last, but still very important parameter, is the call-minute user cost, or user tariff. This is the amount of money charged to the user for each minute that he or she uses the network, and it is very difficult to quantify, since it depends upon the economic planners' break-even expectations.

Pricing a service is a difficult task, since the planner is at the hands of the market supply-and-demand variations. A tariff too high will theoretically create large revenue, but an expensive service may stop users from using it, thus lowering traffic intensity and revenue. A tariff too low may be attractive, thus increasing traffic intensity and revenue, but it may take longer (or never) to recover the investment. It will be shown how small variations in traffic intensity and/or user tariffs estimates create very large variations in other system parameters. Sudden variations like these can change completely the outlook of the business plan and the viability of the network.

Network Economic Evaluation Model

Up until now the description of the elements that constitute a satellite communications network has been presented from a mainly technical point of view, considering their impact on network economic planning.

A complete network evaluation model should include all economic parameters mentioned so far, therefore, the total satellite network cost model should include the terms found in (4.16) for VSAT costs, (4.21) for Hub costs and (4.27) for revenues. Networking costs are already included in (4.16) and (4.21). The economic network evaluation model would then be based upon the expected profits (PR), in this case,

$$\text{Profit} = \text{Revenue} - \text{Costs} \tag{4.28}$$

$$PR = RE - TV - TH \tag{4.29}$$

$$PR = RE - \left[V1 + \sum_{T=1}^{Lt} V2 \right] - \left[H1 + \sum_{T=1}^{Lt} H2 \right] \tag{4.30}$$

$$\begin{aligned} PR = {} & \sum_{t=1}^{Lt} N(OT \times CU)\left[{}^{P}\!/_{A}, i, t\right] \\ & - \left[N(CV + IV + FV) + \sum_{T=1}^{Lt} N\left[LV + MV + SV + (AV \times OT)\right]\left({}^{P}\!/_{A}, i, t\right) \right] \\ & - \left[CH + IH + FH + \sum_{T=1}^{Lt} N\left[LH + MH + SH + (AH \times OT)\right]\left({}^{P}\!/_{A}, i, t\right) \right] \end{aligned} \tag{4.31}$$

Notes:

1. It is important to mention that often small satellite networks (<50 nodes) lease hub capacity and connectivity on a larger existing hub from a different network, since owning a hub implies a major capital investment which may not be economically justified for a small network. For that reason a term is included in both equations (9) and (13) as variable expenses in case either segment is not owned.
2. The PSTN access fee (*AV, AH*) needs to be paid only once since it is the accessing point to the PSTN and that only takes place at the hub, so the VSAT proportional cost may be specified as *AV = $0*.
3. Traffic intensity estimation (*TS*) is application-dependent, will be different for each earth station in a real network, and will vary from network to network. A common way to go around the specifics is to find a conservative traffic intensity figure from previous similar experiences, and assume a uniform distribution of traffic at all network nodes.

Fixed SCPC networks have the same number of nodes and satellite channels, therefore any earth station with a low usage time will actually be generating expenses instead of revenue, which is not a good idea when planning a telecommunications network.

Table 2.5 shows in a succinct way the mathematical equations (4.13) to (4.31) developed in this research for the Fixed-SCPC economic model.

Table 4.6. Fixed-SCPC satellite network economic model.

	Remote nodes (VSATs)	*Hub*	*Networking*
Initial cost	$V1 = N\,(CV + IV + FV)$	$H1 = CH + IH + FH$	$NV = \sum_{t=1}^{Lt} N(AV \times OT)\left[{}^{P}\!/_{A}, i, t\right]$
Operational cost	$V2 = N\,[LV + MV + SV + (AV \times OT)]$	$H2 = LH + MH + N[SH + (AH \times OT)]$	$NH = \sum_{t=1}^{Lt} N(AH \times OT)\left[{}^{P}\!/_{A}, i, t\right]$
Total cost	$TV = V1 + \sum_{t=1}^{Lt} V2$	$TH = H1 + \sum_{t=1}^{Lt} H2$	OT = TS × AT
VSATs cost	$TV = N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV + SV + (AV \times OT)]]\}\left({}^{P}\!/_{A}, i, t\right)$		
Hub cost	$TH = CH + IH + FH + \sum_{T=1}^{Lt} [LH + MH + N\{SH + (AH \times OT)\}]\left({}^{P}\!/_{A}, i, t\right)$		
Revenue	$RE = \sum_{t=1}^{Lt} N(OT \times CU)\left[{}^{P}\!/_{A}, i, t\right]$		
Profits	$PR = \sum_{t=1}^{Lt} N(OT \times CU)\left[{}^{P}\!/_{A}, i, t\right]$ $-\left[N(CV + IV + FV) + \sum_{T=1}^{Lt} N[LV + MV + SV + (AV \times OT)]\left({}^{P}\!/_{A}, i, t\right)\right]$ $-\left[CH + IH + FH + \sum_{T=1}^{Lt} [LH + MH + N\{SH + (AH \times OT)\}]\left({}^{P}\!/_{A}, i, t\right)\right]$		

4.4.3.2 Fixed-MCPC

A Multiple Channel per Carrier (MCPC) satellite system allows an earth station to provide telephone service to more than one user per link, since Time Division Multiplexing technology allows that channel to be shared by several users. As mentioned in Section 2.4.2.1, available technology allows multiplexing of up to 8 and 10 Time Division Multiplex (TDM) user channels into a single 64 kbps carrier. MCPC systems are believed to improve not only the capacity but also the revenue of an earth station, but at a cost for the network investors.

Figure 4.4 shows the satellite network with a star topology and a single carrier per earth station, but with the capacity to multiplex eight TDM channels into each carrier, thus transmitting a MCPC signal to the hub per frequency.

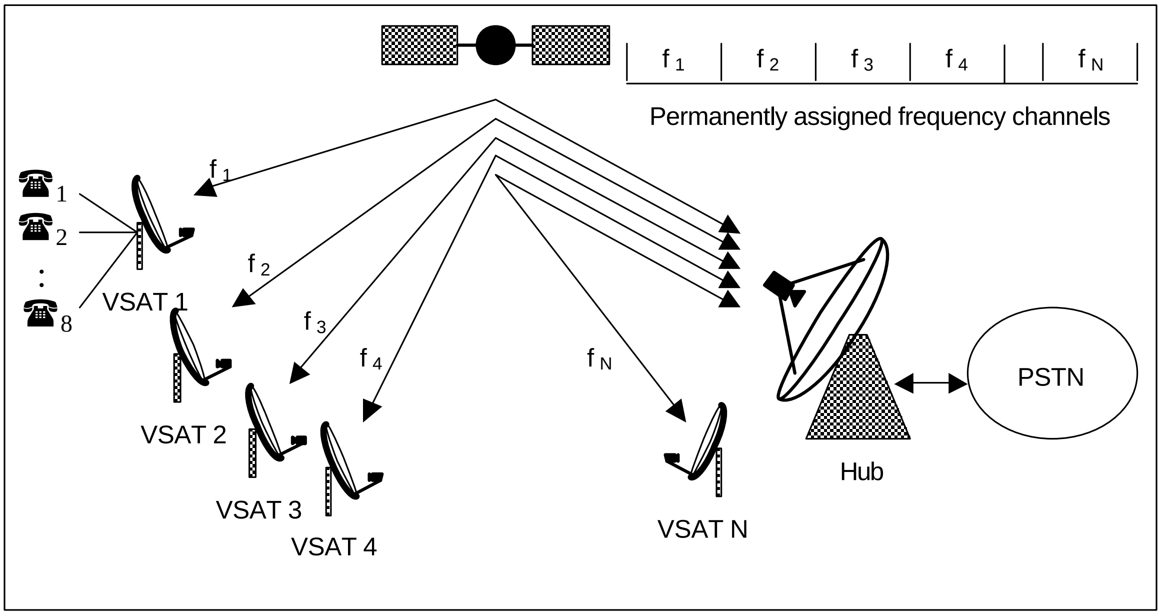


Figure 4.4. Fixed MCPC satellite network.

In this case, a MCPC model is developed assuming a Fixed-SCPC access to the satellite in a star topology, very similar to the model explained in the previous Section 4.4.3.1, on Fixed SCPC methodology for network design. The only difference here is that the 64 kbps satellite signal will carry $r = 8$ TDM compressed voice channels, each with an assumed individual traffic of 0.05 Erlangs. The initial investment as well as the operational expense follows the same model as the previous model, except that in this case the individual cost of the remote earth stations (VSATs) and the hub is assumed to be 50% higher. This is because a more complex user interface is supplied with each earth station, with a number of telephone sets, voice coders and TDM capabilities per terminal that increase the VSATs and hub cost.

A MCPC system will continue to use (and pay for) a single satellite carrier for up to eight voice channels, thus saving transponder bandwidth, but requiring more power from both the earth station and the satellite and perhaps larger antennas. The maintenance expenses are assumed the same as in other configurations. The PSTN access fee will be charged according to the number of voice channels actually accessing the network, not by the number of satellite carriers. Therefore the cost for PSTN access is larger than in other configurations, but the expected revenue is also proportional to the number of voice channels.

As mentioned before, a Fixed-MCPC system may be attractive only if medium to high traffic is expected on the network, otherwise the larger initial investment will create a heavy burden on expected profits. Let's not forget that an MCPC earth station costs more than a simple earth station, and only one voice channel is necessary to pay for the full transponder channel. In a low traffic network a single user in the carrier would pay for the whole channel, which would increase the user cost lowering traffic even more and investors would never recover the initial investment. For that reason, an MCPC-DAMA system is not even considered in this work.

Still for PSTN access and revenue intent a user traffic probability must be found to define the economic model. Assuming an expected traffic of 0.05 Erlang per user in an eight-channel TDM terminal, the number of possible simultaneous calls following a binomial distribution, leads to a probability $p_r(1) = 0.2793$ for at least one user using the satellite channel and $p_r(2) = 0.0514$ or less for $r = 2$ users. This work considers $TS_{user} = 0.05$ Erlang for each r_i user in this model to obtain operational time (OT).

Table 4.7 shows the mathematical equations developed in this research for the Fixed-MCPC satellite network model. The sequence to implement the Fixed MCPC economic model is the same as that presented in Section 4.4.3.1 for the Fixed-SCPC model; only the equations vary.

Table 4.7. Fixed-MCPC satellite network economic model.

	Remote nodes (VSATs)	*Hub*	*Networking*
Initial cost	$V1 = N\,(CV + IV + FV)$	$H1 = CH + IH + FH$	$NV = \sum_{t=1}^{Lt} N(r \times AV \times OT)\left[P/_{A}, i, t\right]$
Operational cost	$V2 = N\,[LV + MV + SV + (r \times AV \times OT)]$	$H2 = LH + MH + N\,[SH + (r \times AH \times OT)]$	$NH = \sum_{t=1}^{Lt} (r \times AH \times OT)\left[P/_{A}, i, t\right]$
Total cost	$TV = V1 + \sum_{t=1}^{Lt} V2$	$TH = H1 + \sum_{t=1}^{Lt} H2$	$\mathrm{OT} = \mathrm{r} \times \mathrm{TS}_{\mathrm{user}} \times \mathrm{AT}$
VSATs cost	$TV = N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV + SV + (r \times AV \times OT)]\}\left(P/_{A}, i, t\right)$		
Hub cost	$TH = CH + IH + FH + \sum_{T=1}^{Lt} [LH + MH + N\{SH + (r \times AH \times OT)\}]\left(P/_{A}, i, t\right)$		
Revenue	$RE = \sum_{t=1}^{Lt} N(r \times OT \times CU)\left[P/_{A}, i, t\right]$		
Profits	$PR = \sum_{t=1}^{Lt} N(r \times OT \times CU)\left[P/_{A}, i, t\right]$ $- \left[N(CV + IV + FV) + \sum_{T=1}^{Lt} N[LV + MV + SV + (r \times AV \times OT)]\left(P/_{A}, i, t\right)\right]$ $- \left[CH + IH + FH + \sum_{T=1}^{Lt} [LH + MH + N\{SH + (r \times AH \times OT)\}]\left(P/_{A}, i, t\right)\right]$		

4.4.3.3 SCPC-DAMA

As mentioned in Section 2.4.2.1 describing topologies, Single Channel per Carrier (SCPC) is probably the most popular multiple access protocol for rural satellite applications. When SCPC is joined by an efficient demand assignment protocol such as Demand Assignment Multiple Access (DAMA), the network's efficiency increases by carefully controlling the access to the channels. SCPC-DAMA has become the multiple access technique of choice in satellite rural telephony applications due to its ease of implementation and the efficient use of the satellite channel.

Here both earth stations are assigned a narrowband channel onboard the satellite during the length of the call, from a limited pool of *n* channels, and when the communication session is over, both earth stations release their channels. Since the Erlang B formula helps define the correct number of *n* channels for a certain network size of *N* nodes and a grade of service *GoS*, the model considers all three factors to provide the correct network design information.

Figure 4.5 shows how a SCPC DAMA satellite network is connected to the PSTN.

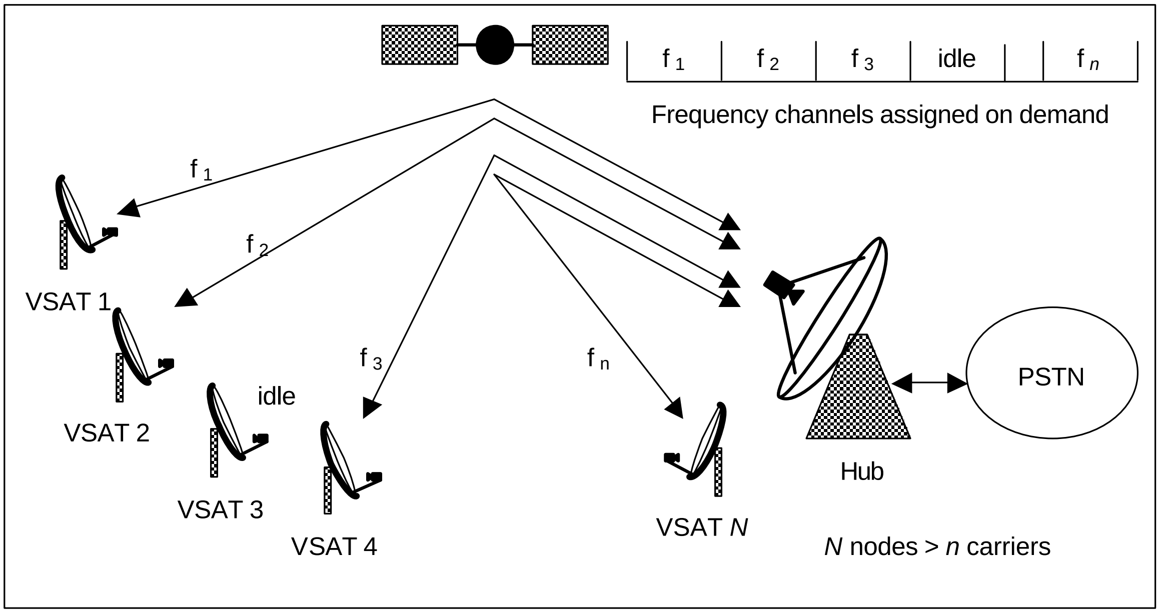


Figure 4.5. SCPC DAMA satellite network

In the SCPC-DAMA case, the initial network cost is still completely influenced by the size of the network, including operational cost such as licensing and maintenance. The advantage of SCPC-DAMA over Fixed-assignment SCPC is that only a few earth stations, the active ones, are using the satellite channels, which lowers the satellite channel cost that idle Fixed-SCPC stations must pay at all times. Although idle SCPC-DAMA earth stations are not generating revenue, and still requiring maintenance, the profit from a SCPC-DAMA network depends largely on the generated traffic. A high traffic SCPC-DAMA network may be very profitable if properly dimensioned and correctly designed, even under low or medium traffic intensity.

In all cases throughout this research work a Grade of Service figure of 1% to 2% has been observed, with a tendency to recommend the number of trunks or satellite channels closest to the 2% figure, for economic reason only. It is assumed that if the GoS worsens from 1.5% to 1.8%

at the cost of one or two carriers, it is still a valid sacrifice of network quality (from one blocked call in 67 to one in 55).

Table 4.6 shows the mathematical equations developed for the SCPC-DAMA economic model, where *n* is the number of satellite carriers and *N* is the total number of network nodes or earth stations. This is assuming a star topology with single hop links between the hub and VSAT only; no VSAT-to-VSAT double hops are considered in this work. The sequence to implement the SCPC-DAMA economic model is the same as that presented in Section 4.4.3.1 for the Fixed-SCPC economic model, only the equations vary.

Table 4.8. SCPC-DAMA satellite network economic model.

	Remote nodes (VSATs)	*Hub*	*Networking*
Initial cost	$V1 = N\,(CV + IV + FV)$	$H1 = CH + IH + FH$	$NV = \sum_{t=1}^{Lt} n(AV \times OT)\left[P/A, i, t\right]$
Operational cost	$V2 = N\,[LV + MV] + n[SV + (AV \times OT)]$	$H2 = LH + MH + n[SH + (AH \times OT)]$	$NH = \sum_{t=1}^{Lt} n(AH \times OT)\left[P/A, i, t\right]$
Total cost	$TV = V1 + \sum_{t=1}^{Lt} V2$	$TH = H1 + \sum_{t=1}^{Lt} H2$	OT = TS × AT
VSATs cost	$TV = N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV] + n[SV + (AV \times OT)]\}\left(P/A, i, t\right)$		
Hub cost	$TH = CH + IH + FH + \sum_{T=1}^{Lt} \{LH + MH + n[SH + (AH \times OT)]\}\left(P/A, i, t\right)$		
Revenue	$RE = \sum_{t=1}^{Lt} n(OT \times CU)\left[P/A, i, t\right]$		
Profits	$PR = \sum_{t=1}^{Lt} n(OT \times CU)\left[P/A, i, t\right] - \left[N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV] + n[SV + (AV \times OT)]\}\left(P/A, i, t\right)\right] - \left[CH + IH + FH + \sum_{T=1}^{Lt} \{LH + MH + n[SH + (AH \times OT)]\}\left(P/A, i, t\right)\right]$		

4.4.3.4 Mesh SCPC-DAMA

The mesh topology allows full point-to-point connectivity, thus transferring information between any two nodes in a network with minimum delay. In a satellite network with N nodes the number of required connections is $N(N-1)$ carriers, or one satellite link to every network earth station. A full-meshed satellite network with fixed assignment access would imply that there are $N(N-1)$ transponder channels permanently assigned to this network and that each earth station has $N-1$ transmitters and $N-1$ receivers, which is obviously impractical. Besides being an expensive option regarding satellite channel cost if N is large, it would require a reallocation of the number of transmitters and receivers at each earth station every time the network incorporates a new earth station.

The fixed-assignment mesh topology assumes a requirement for permanent full connectivity by each earth station, which is not the case in most applications. Most of today's commercial meshed networks are based on demand assignment SCPC, where any earth station requests a temporary connection to another earth station through a common signaling channel and a control earth station. The control earth station replies by allocating satellite resources to both the calling and the called earth stations. This requires only an arbiter control earth station and for each earth station node to be equipped with dynamic frequency radios to provide the assigned transmit and receive frequency pairs.

Most cases in rural telephony do not require a full mesh topology, since villagers are assumed to call the PSTN more often than one other. The reason a mesh topology is used in rural networks is mainly due to the use of regional gateways that allow connection of the call to the PSTN gateway closest to the destination site, reducing long distance costs inside the PSTN.

A properly designed mesh network allows the users to benefit from lower cost calls, but it requires larger earth stations for gateway operation, called Gateway Earth Stations (GES) or mini-hubs. Gateways are able to carry a number of simultaneous telephone calls into the PSTN and meshed gateways can provide reliability to the network in case of gateway or PSTN failure.

A certain number of carriers m (and their corresponding transponder space) may be assigned to each GES so that each remote earth station can access the PSTN through that specific gateway over a locally defined pair of carriers. The traffic capacity for each GES is defined by a traffic analysis depending upon expected traffic routes leading to a number of gateways.

A network with N nodes is serviced by n satellite carriers with m carriers per GES managed by the control earth station. Any GES can take the control function. Assuming a similar distribution of traffic for each GES, all gateways carry the same number of carriers on demand and thus generate similar expenses and revenue. Therefore, the total satellite capacity required (and the number of simultaneous telephone calls over the network) is

$$n = g \times m \tag{4.32}$$

where n is the number of satellite carriers (and telephone calls), g is the number of gateways and m is the number of carriers per gateway.

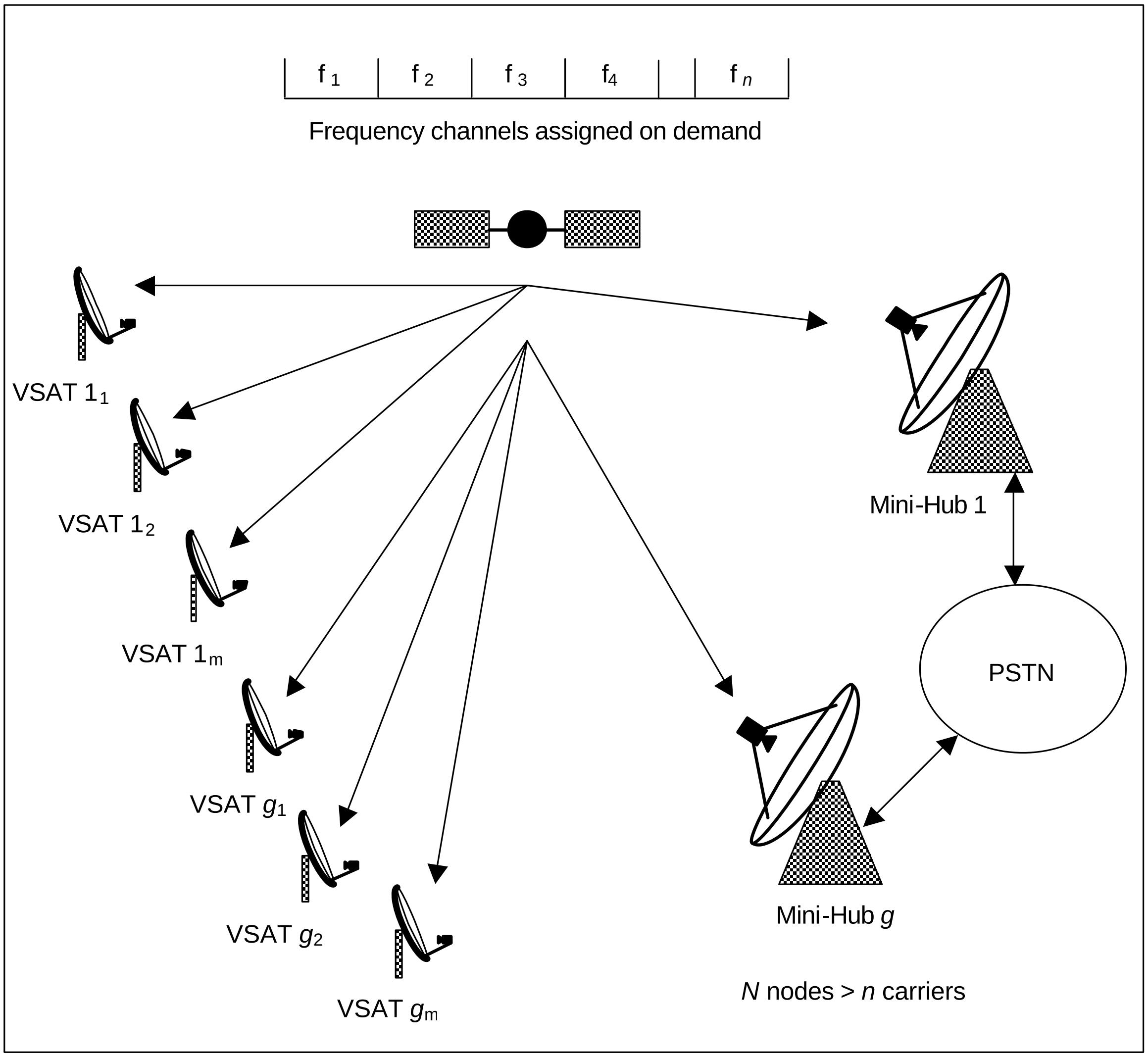


Figure 4.6. Mesh SCPC DAMA satellite network with g gateways or mini-hubs.

Although no prices for GES were available, it is assumed that their cost may be proportional to their traffic capacity. An estimated cost of $100,000 per mini-hub with a traffic capacity of 25 voice channels per 100 nodes with a 1.3 % GoS is assumed in this model. Table 4.9 shows the mathematical equations developed here for a mesh SCPC-DAMA economic model.

The sequence to implement the Mesh SCPC-DAMA economic model is the same as that presented in Section 4.4.3.1 for the Fixed-SCPC economic model; only the equations vary.

Table 4.9. Mesh SCPC-DAMA satellite network economic model.

	Remote nodes (VSATs)	*Hub*	*Networking*
Initial cost	$V1 = N(CV + IV + FV)$	$H1 = g[CH + IH + FH]$	$NV = \sum_{t=1}^{Lt} n(AV \times OT)[P/A, i, t]$
Operational cost	$V2 = N[LV + MV] + n[SV + (AV \times OT)]$	$H2 = g[LH + MH] + n[SH + (AH \times OT)]$	$NH = \sum_{t=1}^{Lt} (AH \times OT)[P/A, i, t]$
Total cost	$TV = V1 + \sum_{t=1}^{Lt} V2$	$TH = H1 + \sum_{t=1}^{Lt} H2$	$OT = TS \times AT$
VSATs cost	$TV = N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV] + n[SV + (AV \times OT)]\}(P/A, i, t)$		
Hub cost	$TH = g[CH + IH + FH] + \sum_{T=1}^{Lt} (g[LH + MH] + n[SH + (AH \times OT)])(P/A, i, t)$		
Revenue	$RE = \sum_{t=1}^{Lt} n(OT \times CU)[P/A, i, t]$		
Profits	$PR = \sum_{t=1}^{Lt} n(OT \times CU)[P/A, i, t] - \left[N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV] + n[SV + (AV \times OT)]\}(P/A, i, t)\right] - \left[g[CH + IH + FH] + \sum_{T=1}^{Lt} \{g[LH + MH] + n[SH + (AH \times OT)]\}(P/A, i, t)\right]$		

4.4.3.5 OBP Regenerative Satellites

So far the models discussed have dealt with repeater-only (bent-pipe) satellites, which means that at the satellite the analog waveform is only amplified and translated in frequency for the downlink. No other function is performed at the transponder. Newer satellites provide the option of signal processing onboard the satellite, increasing the signal's quality and overall performance. This research includes the simplest of the processing functions that the new satellites are including, which is the digital signal's regeneration.

Onboard Processing (OBP) refers to functions that can be performed on board the satellite to the information signal, as mentioned in Chapter 3. These functions include demodulation/re-modulation, error encoding/decoding, transponder or beam interconnection/switching, demultiplexing/re-multiplexing, packet/frame/cell switching, clock generation/regeneration and several other possible functions.

Some of the functions mentioned above need to be processed in real time, while others can be processed in non-real time with onboard storage. Since the goal of the present research is to provide alternatives for voice (telephone) applications, and since current packet-switching technology does not provide the required QoS guarantees yet, only an OBP regenerative satellite is considered in the economic models. This type of transponder performs demodulation, error correction and re-modulation functions on the digital signal in a processing transponder.

A regenerative payload performs onboard demodulation of the uplink carriers, then regenerates the correct bit stream obtained from demodulation and a new carrier modulates the signal again for downlink. This new carrier is noise-free, so the regenerative payload does not retransmit the uplink noise on the downlink, improving the overall quality.

[Mar97] reports that a typical regenerative satellite can provide between 2 dB and 5 dB reduction in overall Eb/No with respect to a transparent repeater satellite assuming the signal is regenerated onboard the satellite. A satellite with OBP capability essentially separates uplinks from downliks, having two channels with cascading bit error rates, so the total bit error rate is

$$P_b = P_u + P_d - 2\,P_u\,P_d \approx P_u + P_d \qquad (4.33)$$

where P_b is the total BER, P_u is the uplink BER and P_d is the downlink BER.

Several advantages emerge with an improved BER in a satellite network.

1. Smaller earth stations can be used with reduced EIRP and G/T for an equivalent service quality, reducing the initial cost of a network.

2. A higher bit rate may be used on the downlink if an efficient spectrum modulation (e.g. 16- or 64-QAM) is used on the same channel bandwidth, increasing potential revenue.
3. A lower transmit power is required from the transponder for the same bit rate and bandwidth while keeping the required network QoS requirements, allowing more carriers on the satellite, or operating the HPA away from the non-linear region, thus avoiding intermodulation interference.

Table 4.10. On-Board Processing (regenerative) satellite, fixed SCPC, star network economic model.

	Remote nodes (VSATs)	*Hub*	*Networking*
Initial cost	$V1 = N\,(CV + IV + FV)$	$H1 = CH + IH + FH$	$NV = \sum_{t=1}^{Lt} N(AV \times OT)\left[P/A, i, t\right]$
Operational cost	$V2 = N\,[LV + MV + SV + (AV \times OT)]$	$H2 = LH + MH + N[SH + (AH \times OT)]$	$NH = \sum_{t=1}^{Lt} N(AH \times OT)\left[P/A, i, t\right]$
Total cost	$TV = V1 + \sum_{t=1}^{Lt} V2$	$TH = H1 + \sum_{t=1}^{Lt} H2$	OT = TS × AT
VSATs cost	$TV = N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV + SV + (AV \times OT)]\}(P/A, i, t)$		
Hub cost	$TH = CH + IH + FH + \sum_{T=1}^{Lt} \{LH + MH + N[SH + (AH \times OT)]\}(P/A, i, t)$		
Revenue	$RE = \sum_{t=1}^{Lt} N(OT \times CU)\left[P/A, i, t\right]$		
Profits	$\begin{aligned} PR = {} & \sum_{t=1}^{Lt} N(OT \times CU)\left[P/A, i, t\right] \\ & - \left[N(CV + IV + FV) + \sum_{T=1}^{Lt} \{N[LV + MV + SV + (AV \times OT)]\}(P/A, i, t)\right] \\ & - \left[CH + IH + FH + \sum_{T=1}^{Lt} \{LH + MH + N[SH + (AH \times OT)]\}(P/A, i, t)\right] \end{aligned}$		

In this work an OBP regenerative satellite is assumed to have the same bandwidth and transmit power at the Ka frequency band (30/20 GHz), allowing a comparison between current commercial technology for network. Table 4.10 shows the mathematical equations developed for an OBP (regenerative) satellite, fixed SCPC, star network economic model.

The sequence to implement the OBP regenerative satellite economic model is the same as that presented in Section 4.4.3.1 for the fixed-SCPC economic model. The model for the bent-pipe and OBP satellites is the same since topology and multiple access are the same. Satellite costs increase and VSAT costs decrease, but the model is the same, only the input values change.

4.4.4 Evaluation Design

The different models presented in Section 4.4.3 describe the equations needed to evaluate the economic impact of different topologies and multiple access in the process of telephone network design via satellite. The different models were implemented in a number of Microsoft Excel 97® spreadsheets that allowed individual analysis in four areas for each model. Following the Excel® terminology, an individual Excel® file has an extension .xls, called a “workbook”, with a workbook having as many “worksheets” as it may need. As part of this research a number of Matlab programs were initially developed, but it was decided that Excel® was a better option for the type of work and analysis required. Besides having the basic mathematical operations, Excel® also provides plenty of financial, engineering and scientific functions as part of its extended libraries, including optimization commands that provide the Excel® user with a very powerful analysis tool. Next, a brief description of the implementation of each computer model is presented for satellite rural telephone network design.

4.4.4.1 Computer Model Description

This section will describe the computer models for performance optimization. The computational model was created to manipulate a number of specific-case parameters used as input data with the proposed economic models as shown in Figure 4.7. A number of control parameters are introduced as constraints, allowing the optimization process to remain bounded. The set of optimization parameters are used to maximize or minimize the performance during the design process on any one of several topics (traffic capacity, user cost, network size, etc.) The outcome of the process defines which model best solves the specific problem according to the desired optimization parameters.

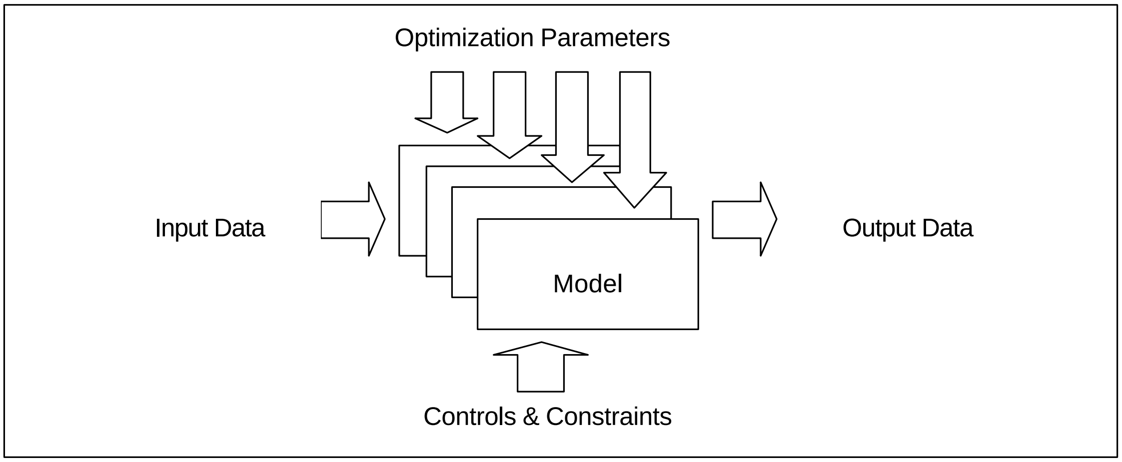


Figure 4.7. Satellite rural telephone network design optimization model

The models were implemented in a workbook for each model, with a set of four worksheets in each case. The reason for this distribution was to separate the specific functions of each worksheet as part of the whole program, with similar functions in all cases but individual characteristics for each model, shown in flow charts in Figure 4.8. The four parts of each workbook are described next.

1) A *Front* worksheet, with the input information about the desired network general parameters, including number of nodes, application requirements, equipment cost and projected system lifetime.
2) A *Cost* worksheet, with the implementation of the equations described in Section 4.4.3 for each one of the economic models, including time value of money and other economic functions. The values used in these worksheets were previously defined at the beginning of Chapter 4, along with Performance metrics and Network planning factors.
3) A *Traffic* worksheet, with the implementation of the Erlang B equation as a function of the input parameters introduced in the Front worksheet, and related to network size, number of nodes, user traffic and expected Grade of Service.
4) A *Link* worksheet, with the implementation of the satellite link budget described in Section 2.2.1, in order to guarantee that the satellite and earth station's performance specifications were met before the actual economic design. The parameters evaluated here were mainly related to transponder capacity, earth station size, signal quality and performance, system availability and bit error rate.

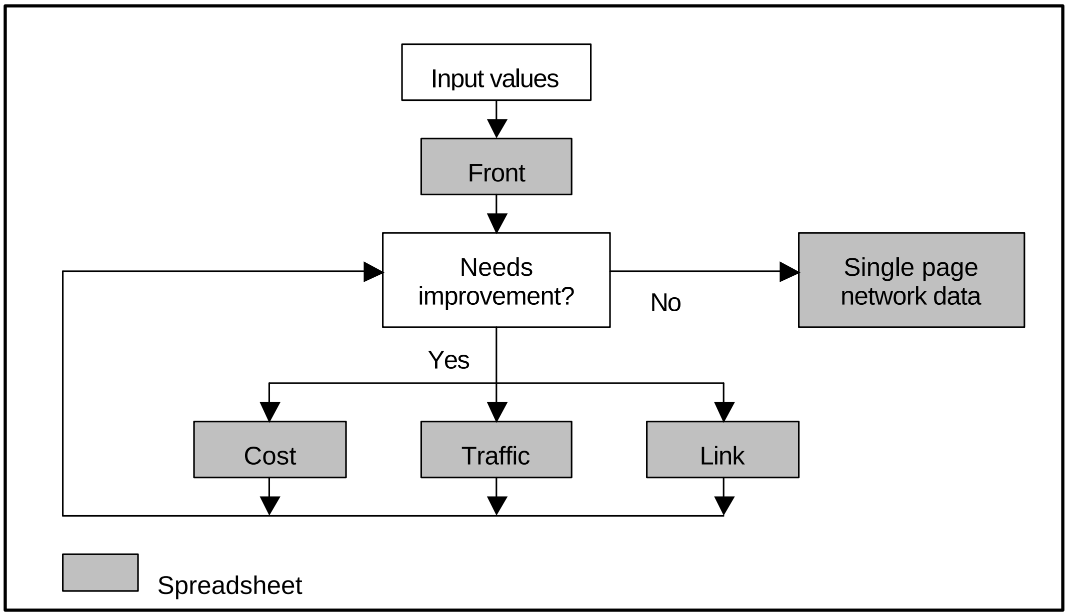


Figure 4.8 Network economic model flowchart

4.4.4.2 Pivoting

Once all the models were implemented in their workbooks, a single spreadsheet with a final network design was created for each model in order to provide all relevant information in a single page. This spreadsheet includes tables and charts that allow fine-tuning of the economic design, thus predicting possible outcomes for different network projections over the entire network's lifetime. This spreadsheet allows the network designer to have a "big picture" of the desired network's future economic performance, but only under strictly limited assumptions.

The spreadsheet works by assigning a specific parameter with a reasonable value, thus defining that parameter as the controlling parameter once the desired network has been designed. The controlling parameter (or pivot) has a direct impact on the desired "to be optimum" parameter, which is the parameter whose performance we wish to minimize or maximize. The optimization process takes place by "pivoting" with the optimization functions that Excel® provides, allowing the network designer to "play" with many variations until an optimal solution is found, according to the network designer's requirements or constraints.

Once the desired parameter's optimal value is found, a number of projections can be made, basically regarding network size and expected traffic increments, in order to predict the behavior of the network under changing conditions. It is important to clarify that the projections are valid only under the pivot's (controlling parameter's) assumed values. A change in the network model parameters during its implementation or operational lifetime may have a significant variation with those predicted during this stage of the network planning and design process.

An important aspect, not easily seen by the planner once the model is working, is that there is no way to know for sure when a change in the pivot will produce a result outside of the feasible solution region. A number of trial and error computer runs helps to find out the pivoting values that provide feasible solutions for the optimization problem.

4.4.4.3 Generation of Results

The results generated by the computer for the satellite network models have the convenience that they are based upon analytical models, therefore not requiring the extensive computational time that is so common in large network simulation. Although the Excel® optimizing functions perform a rather large number of iterations before finding the optimal value, their algorithms converge reasonably quick, taking only a few seconds to show whether or not a feasible solution exists for that problem. Every change of value of a parameter in the spreadsheet generates instantaneously a number of tables and graphs that include the new results, derived from the parameter changed.

Another advantage of using Excel® is that it offers a wide selection of visual aids that allow a better understanding of the network's performance and lifetime operational behavior. The results generated by the different models can easily be presented in various displays, from tables to graphs to charts, providing the network designers and decision takers with a quick view of the general network situation, projections and potential outcomes. Finally, the results can be extracted from the spreadsheets and transferred to practically any user application

4.5 Summary

This chapter has presented the development of a methodology for efficient satellite telephone network design based on different analytical models. The development of the analytical model required that the scope of the problem be limited and a number of parameters, performance metrics and system boundaries be assumed. The design philosophy and derivation of the analytical models is explained, as well as the basic tools for optimization algorithms.

The process to implement a set of computer program sequences over spreadsheets is explained, as well as the general behavior of the analized models. Finally, the input parameters and measured outputs of the models were explained.

Chapter 5

Parametric Analysis Results

This chapter presents the results obtained during the parametric analysis of the models analyzed in this work. It compares the economic performance of the different topologies and multiple access and its impact on satellite telephone network design. It is divided into four sections. Section 5.1 presents the results of the different economic models for different scenarios. Section 5.2 compares each model in its technical and economic performance behaviors, allowing some interesting observations. Section 5.3 discusses the predictive power of these models and their possible impact on satellite network economic analysis. Section 5.4 is a summary of the parametric analysis results.

Section 5.1 presents the analysis results of the Fixed-SCPC economic model, the Fixed-MCPC economic model, the SCPC-DAMA economic model, the Mesh-SCPC and the OBP regenerative economic models. All parametric analysis are shown for a low traffic (pessimistic), a medium traffic (nominal) and a high traffic (optimistic) scenario, with changing projections in each case.

Section 5.2 discusses the results shown in Section 5.1, further discussing the sensitivity of the models to small variations on traffic intensity, network size, satellite transponder capacity and user cost-per-minute.

Section 5.3 analyzes the predictive power of the economic models, allowing for a discussion of the most commons errors found when planning and designing satellite telephone networks, and their impact on the finished network operation.

Finally, Section 5.4 summarizes the results obtained in this chapter, as well as the tendencies and sensitive parameters observed during the analysis and design process.

5.1 Parametric Analysis Results of the Economic Models

This section presents the different economic models developed as part of the research on the optimal design of rural satellite telephone networks. Parametric analysis tools allow the analytical study of a system or network parameters with ease and convenience, allowing quick observation of the system behavior (analysis) and its most desired performance (optimization).

The traffic intensity parameters to set low, medium and high traffic loads for the parametric analysis are based on 0.05 Erlangs for low traffic (3 min/hr), 0.15 Erlangs for medium traffic (9 min/hr) and 0.25 Erlangs (15 min/hr) for high traffic. A network size of 100 nodes is assumed at all times for analysis purposes, although the projections allow for both smaller and larger network sizes. It is about these values that the optimization process takes place, by pivoting on the expected lifetime breakeven results.

An operational lifetime of 10 years is assumed in all cases, with a yearly interest rate of 18 % for future return of investment at the system's end of life. The operational time was based on a 14 hour/day availability of a typical public commerce (8 AM to 10 PM) business, open for public telephone service 365 days a year.

The analyzed models are optimized using the above values as the design input data, but are projected over traffic intensities of 0.025, 0.05, 0.1, 0.2, 0.25 and 0.33 Erlangs, for networks with 20, 50, 100, 200 and 500 earth stations. Refer to Tables 4.1 and 4.3 for more information about these values.

The parametric analysis were performed using Microsoft® Excel 97 SR-2 with the equations presented in Chapter 4, Section 4.4.3, Tables 4.6 to 4.10. The optimization routines were performed by Excel through the "Goal Seek" function, which uses a variant of the Newton algorithm to optimize a specific cell by changing the value of only one other variable. More complex problems involving multiple variables and constraints can be answered with the "Solver" function, also provided by Excel, but that function was not used in this research.

The assumed earth station parameters are 1.2 m antenna, 2W HPA (radio) for remote terminals (VSATs) and varying antenna and radio parameters for the Hub, depending upon the network size.

5.1.1 Fixed-SCPC Model

This Section presents the analysis results of the Fixed-SCPC economic model for a low traffic (pessimistic), a medium traffic (nominal) and a high traffic (optimistic) scenario, with changing projections in each case.

The basic SCPC scenario is shown in Figure 5.1, along with its data tables and performance graphs. The network is composed of 100 nodes with a traffic intensity of 0.15 Erlang. It is easily seen that the small number of nodes causes the VSAT unit price to be

$7,500, a higher figure than that of larger networks, basically due to volume sales from more than 100 earth stations.

The lifetime economic analysis shows the network reaching the break-even point at the end of the tenth year, as planned. That allows the investors to obtain an 18 % yearly return on investment, which already includes the projected profits over banking interest rates.

The 3-Dimensional (3-D) plot shown in Figure 5.1 shows the Profits-vs.-Nodes-vs.-Traffic projections of the network for other values of traffic intensity and network size, obtained from the tale pivot value at the right bottom of the lifetime cost table.

5.1.1.1 Low Traffic Scenario

A low traffic, or pessimistic, scenario is the one that allows the economic projections to succeed with a very low traffic operation over a satellite network.

The 3-D plot on Figure 5.1 shows how a low traffic scenario (0.025 Erlangs) will not only lose money in a small network ($8 million in losses for a 20-VSAT network) but also in a large size network ($271 million losses for a 500 VSAT-network).

The situation does not improve with a small increase in traffic, since up to 0.10 Erlangs (medium expected subscriber traffic) still generates losses at every network size.

5.1.1.2 Medium Traffic Scenario

The same 3-D plot in Figure 5.1 was projected from a medium, or nominal, traffic intensity of 0.15 Erlangs. This specific case was designed so the network's break-even point is met at 0.15 Erlangs of traffic over the system's lifetime for a 100-VSAT network. This means the medium expected, or nominal, traffic scenario is that with the most likely traffic intensity for the network.

In this case, the expected traffic will generate the initially planned network revenue, which is the initial amount presented to the financiers and investors as the targeted goal. Although it may look to be approaching the break - even point, it must be remembered that

Fixed SCPC
Economic Model

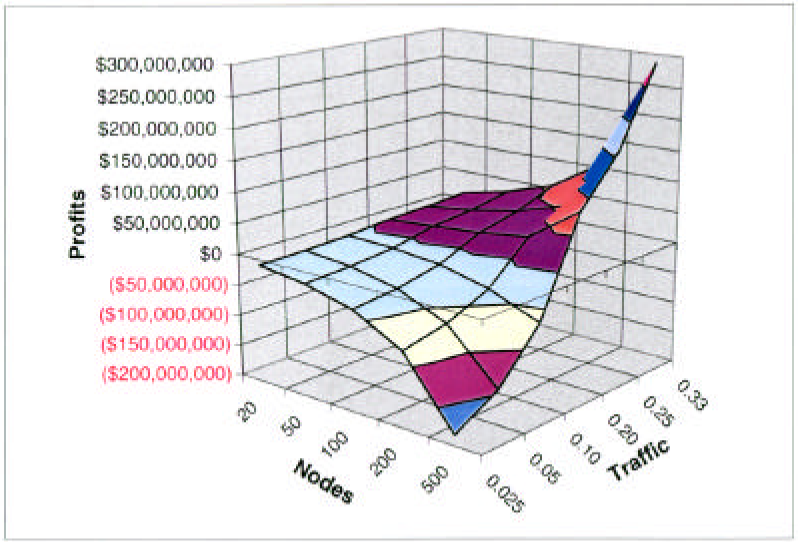
Interest Rate	18%
Number nodes	100
Expected Traffic	0.150
Oper min/yr	45990
Break-even cost	$0.3143

	VSATs	Hub
Unit Price	($7,500)	($40,000)
Installation cost	($1,000)	($10,000)
Unit Lease	$0	$0
Maintenance	($360)	($100,000)
BW ($/carrier)	($5,500)	($550,000)
Fees / Licensing	($100)	($5,000)
PSTN access fee	($0)	$0
Capital costs	($860,000)	($55,000)

	Lifecycle economic analysis				
Year	VSAT Var cost	Hub Var cost	Total costs	Revenue/yr	Profits
1	($769,960)	($650,000)	$2,334,960	$1,445,310	($889,650)
2	($1,422,468)	($1,200,847)	$2,623,316	$2,670,149	($842,816)
3	($1,975,442)	($1,667,667)	$3,643,109	$3,708,149	($777,777)
4	($2,444,063)	($2,063,277)	$4,507,341	$4,587,809	($697,308)
5	($2,841,200)	($2,398,540)	$5,239,740	$5,333,284	($603,764)
6	($3,177,757)	($2,682,661)	$5,860,418	$5,965,043	($499,139)
7	($3,462,974)	($2,923,442)	$6,386,416	$6,500,431	($385,124)
8	($3,704,684)	($3,127,493)	$6,832,177	$6,954,150	($263,150)
9	($3,909,523)	($3,300,418)	$7,209,940	$7,338,658	($134,433)
10	($4,083,115)	($3,446,964)	$7,530,079	$7,664,512	$0

<--- Table pivot

Nodes	Projected traffic intensity (Erlangs)					
$0	0.025	0.05	0.10	0.20	0.25	0.33
20	($8,353,817)	($6,836,231)	($3,801,059)	$2,269,286	$5,304,458	$10,342,844
50	($18,350,440)	($14,556,475)	($6,968,544)	$8,207,317	$15,795,248	$28,391,212
100	($37,939,653)	($30,351,722)	($15,175,861)	$15,175,861	$30,351,722	$55,543,652
200	($80,215,625)	($65,039,763)	($34,688,041)	$26,015,404	$56,367,126	$106,750,985
500	($182,291,286)	($144,351,633)	($68,472,328)	$83,286,284	$159,165,590	$285,125,237



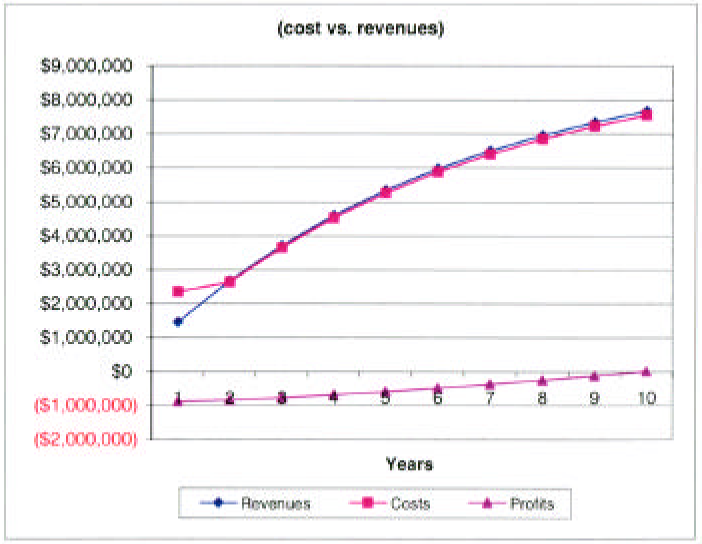


Figure 5.1 Fixed SCPC simulation results

this point already includes a substantial amount of profit due to the larger interest rate used when quantifying the future value of money. Variations on network size will provide only a very small positive difference from the targeted value, so the scenario is still considered as nominal.

5.1.1.3 High Traffic Scenario

From the same 3-D plot in Figure 5.1 is possible to see the projected earnings for a larger-than-expected user traffic behavior, both in terms on network size as well as in terms of expected traffic intensity. The profits for a small network with a high traffic (around 0.25 Erlangs) are substantial ($9 million over the break-even point), even for a small (20 VSAT) network. A larger network provides a dramatically large profit ($271 million over the break-even point) for a 500 VSAT network.

Figure 5.2 shows the comparison of the profit earning curves for low, medium and high traffic analysis. The reason the low traffic curve generates higher profits is that the user cost per minute is much higher. This should not be taken as a way to predict gains, since an expensive system will probably have fewer customers than a more inexpensive system, covering with volume the lower revenue due to higher user cost.

Figure 5.2 also shows the pie charts of the low traffic, medium traffic and high traffic scenarios for a Fixed-SCPC satellite network during the first year of operation, where the VSAT capital investment clearly dominates over the hub capital cost. The VSAT segment also generates more expenses in the variable costs, mainly due to the PSTN access fee for each user channel. It is also easy to see how by increasing the number of calls, or traffic, the variable costs of the VSAT segment particularly increase due to the satellite and connection fees for a larger number of terminals.

It is safe to conclude that, when using Fixed-SCPC satellite modeling analysis, network size defines the general cost of the network and that the network’s operation is expensive. It also is safe to conclude that small Fixed-SCPC networks produce small profits or losses if traffic is low, but generate tremendous losses or profits in large networks. For that reason a careful traffic analysis must be made, considering different network sizes, since a poorly made traffic analysis (or business plan, for that matter) is a sure way to lose money in network planning and design.

Fixed SCPC model

Projected traffic	User cost	0.025	0.05	0.10	0.20	0.25	0.33	VSAT capital	Hub capital	VSAT var	Hub var
Low Traffic	$0.8628	($22,763,792)	$0	$45,527,583	$136,582,750	$182,110,334	$257,686,122	($860,000)	($55,000)	($647,320)	($650,000)
Medium traffic	$0.3143	($37,939,653)	($30,351,722)	($15,175,861)	$15,175,861	$30,351,722	$55,543,652	($860,000)	($55,000)	($769,960)	($650,000)
High traffic	$0.2046	($40,974,825)	($36,422,067)	($27,316,550)	($9,105,517)	$0	$15,115,158	($860,000)	($55,000)	($892,600)	($650,000)

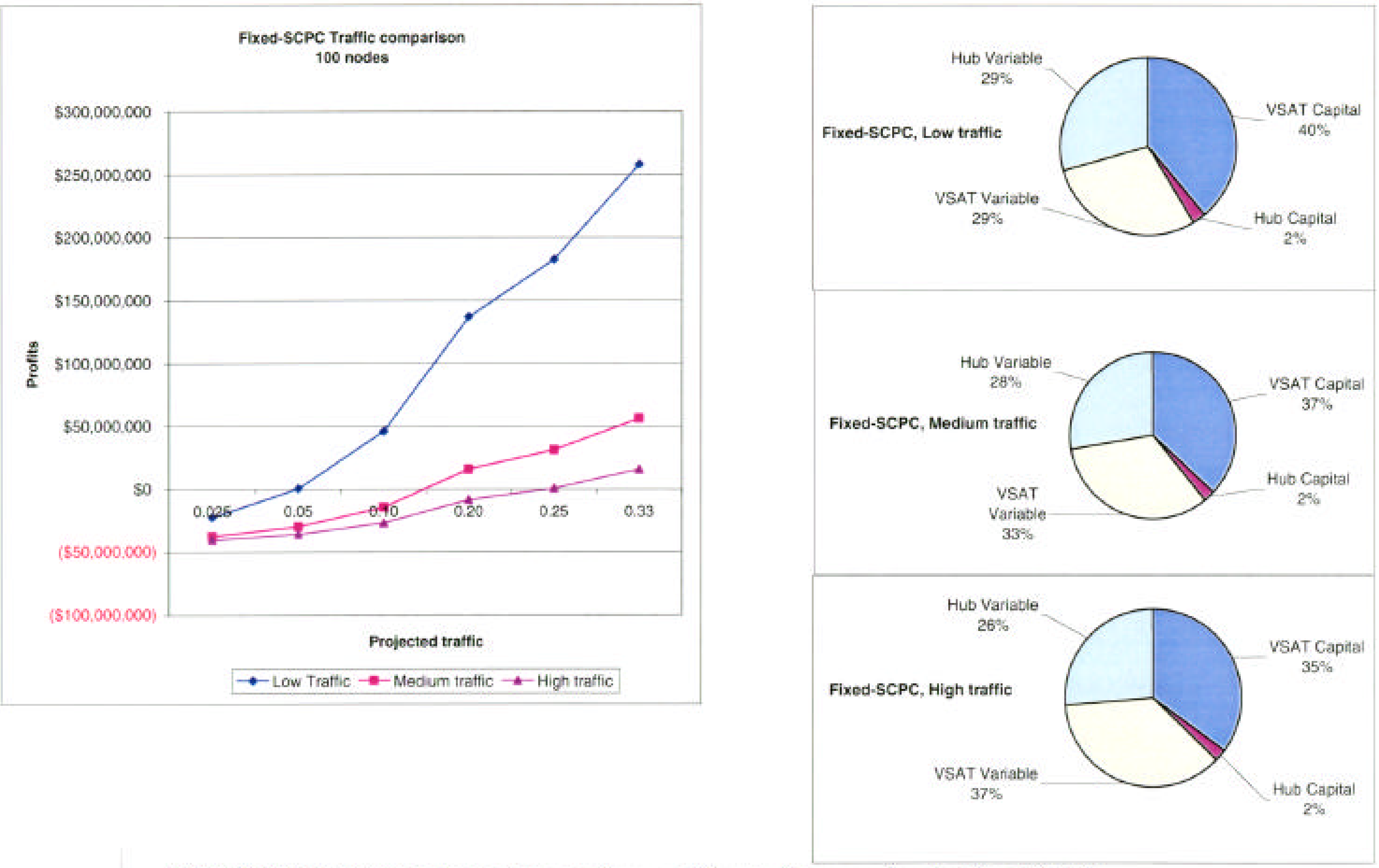


Figure 5.2 Comparison between low, medium and high traffic scenarios for Fixed SCPC

5.1.2 Fixed-MCPC Model

This section presents the analysis results of the Fixed-MCPC economic model for a low traffic (pessimistic), a medium traffic (nominal) and a high traffic (optimistic) scenario with changing projections in each case. There is a small but important difference between the Fixed SCPC model presented in the previous Section 5.1.1 and the Fixed MCPC model presented in this Section. The MCPC earth station has the capability to provide up to eight Time Division Multiplex (TDM) user channels per earth station, while the basic SCPC VSAT only allows one. That does not mean that all eight channels will be operating at the same time; only that it provides the users with more capacity.

The basic MCPC scenario is shown in Figure 5.3, along with its data tables and performance graphs. The network is composed of 100 nodes with a traffic intensity of 0.05 Erlang per TDM user telephone. In this model, the total traffic out of the earth station is the expected traffic intensity per telephone channel, multiplied by the number of active channels at any given time. Although all of the voice channels will use the same satellite carrier, thus saving satellite costs, they still generate expenses by connecting each channel to the PSTN. Besides, each earth station is assumed to cost 50% more than a typical VSAT due to the more complex TDM interfaces and required extra equipment, such as the telephone sets.

There are two economic drivers in this model: the expected user traffic per telephone set and the expected number of active channels at any given time. That problem is treated statistically by means of a binomial distribution function, since the number of events is small (<8). The probability that at least one user is on the line will generate little revenue but still generate the same satellite cost as if all eight lines were busy. Therefore, the expected number of busy lines in this analysis was one line (29% of the time) and two lines (5% of the time).

Again, it is easily seen that the VSAT prices are the dominant figure in the first year. The lifetime economic analysis shows the network reaching the break-even point at the end of the tenth year, as planned. That allows the investors to obtain an 18 % yearly return of investment, which already includes the projected profits over banking interest rates.

Interest Rate		18%	**User stats**
Phones / node		8	1
Exp Traffic/phone		0.15	>> (binom 8 1)
Number nodes		100	V
Exp Traffic / node		0.15	
Oper min/yr		45990	45990
Break-even cost	$	0.3172	

		VSATs		Hub
Unit Price	$	(11,250)	$	(150,000)
Installation cost	$	(1,000)	$	(10,000)
Unit Lease	$	-	$	-
Maintenance	$	(360)	$	(100,000)
BW ($/carrier)	$	(5,500)	$	(550,000)
Fees / Licensing	$	(100)	$	(5,000)
PSTN access fee	$	(0.04)	$	-
Capital costs	$	(1,235,000)	$	(165,000)

Lifecycle economic analysis

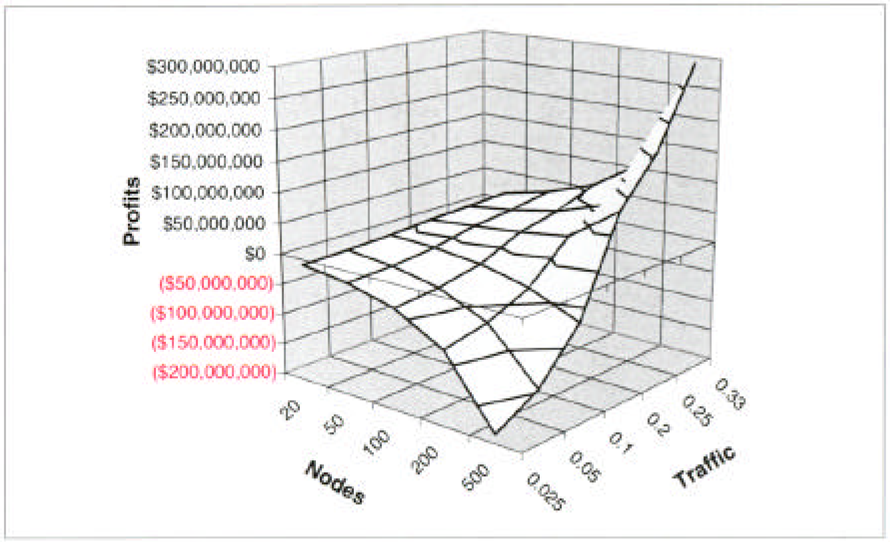
Year	VSAT Var cost	Hub Var cost	Total costs	Revenue/yr	Profits
1	($769,960)	($650,000)	$2,819,960	$1,458,747	($1,361,213)
2	($1,422,468)	($1,200,847)	$2,623,316	$2,694,974	($1,289,555)
3	($1,975,442)	($1,667,667)	$3,643,109	$3,742,623	($1,190,041)
4	($2,444,063)	($2,063,277)	$4,507,341	$4,630,462	($1,066,919)
5	($2,841,200)	($2,398,540)	$5,239,740	$5,382,868	($923,792)
6	($3,177,757)	($2,682,661)	$5,860,418	$6,020,499	($763,710)
7	($3,462,974)	($2,923,442)	$6,386,416	$6,560,865	($589,261)
8	($3,704,684)	($3,127,493)	$6,832,177	$7,018,803	($402,635)
9	($3,909,523)	($3,300,418)	$7,209,940	$7,406,885	($205,690) <--- Table pivot
10	($4,083,115)	($3,446,964)	$7,530,079	$7,735,769	$0

Fixed MCPC
Economic Model

50% more on VSAT, Hub cost

38.5% of the time only
1 users pay BW

nodes	Projected traffic intensity (Erlangs)					
$0	**0.025**	**0.05**	**0.10**	**0.20**	**0.25**	**0.33**
20	($8,437,650)	($6,903,898)	($3,836,392)	$2,298,619	$5,366,125	$10,458,184
50	($18,555,023)	($14,720,641)	($7,051,877)	$8,285,650	$15,954,414	$28,684,562
100	($38,343,820)	($30,675,056)	($15,337,528)	$15,337,528	$30,675,056	$56,135,352
200	($80,853,958)	($65,516,430)	($34,841,374)	$26,508,737	$57,183,792	$108,104,385
500	($184,787,120)	($146,443,300)	($69,755,661)	$83,619,617	$160,307,256	$287,608,737



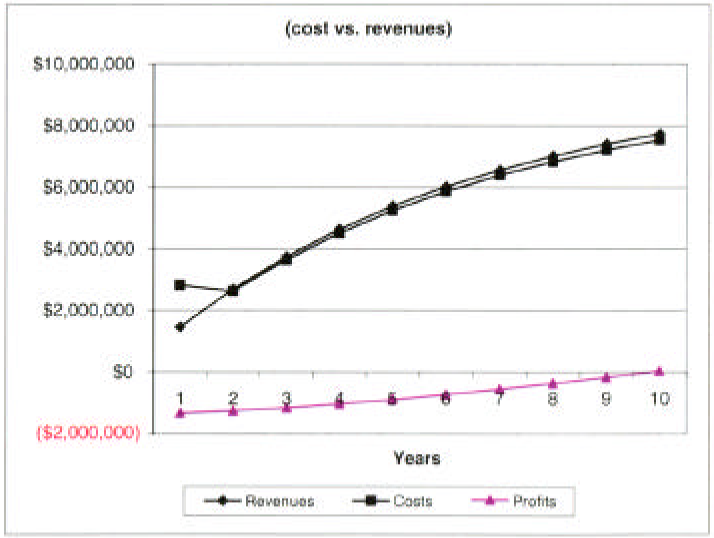


Figure 5.3 Fixed MCPC simulation results for one TDM voice channel per VSAT

The 3-Dimensional (3-D) plot shown in Figure 5.3 shows the profits-vs.-Nodes-vs.-Traffic projections of the network for other values of traffic intensity and network size, obtained from the table pivot value at the right bottom of the lifetime cost table. Two different plots come out from the analysis, the first for one active voice channel, and the other for two active channels.

5.1.2.1 Low Traffic Scenario

A low traffic scenario in a Fixed MCPC model is one that includes minimum use of the earth station (one user) at minimum traffic intensity (0.05 Erlang). By multiplying the total traffic out of the earth station, the analyzed model allows economic projections for very low traffic operation on the satellite network.

The 3-D plot on Figure 5.3 shows how the behavior of Fixed MCPC is very similar to that of the Fixed SCPC model; both plots are practically the same except for the higher earth station costs and higher revenue. A low traffic scenario (0.025 Erlangs) will cause losses in a small network ($8 million loss for a 20-VSAT network) even if only one user is using the channel. Again, this is especially critical in a large size network ($184 million loss for a 500 VSAT-network).

The situation does not improve with a second user, since the total increase in traffic in the earth station requires a longer time to recover the costs. A user traffic of 0.10 Erlangs (medium expected subscriber traffic) produces a total of 0.20 Erlang per VSAT, but still generates losses under that traffic value.

5.1.2.2 Medium Traffic Scenario

Even when the user traffic increases in a Fixed SCPC network, it is still very difficult to generate profits since the PSTN access fees for the second lines adds onto the other network expenses.

Probably the most important improvement in having a second (or third, or more) user simultaneously is not found in the total recovery of investment economics, but rather in the lower user price, as shown in Figure 5.4. Even when presenting the same user traffic (0.15 Erlang), having a second caller per earth station lowers the user cost, in this case from $0.3172 to $0.1093, but it also reduces the overall profit of the network.

Interest Rate		18%	**User stats**
Phones / node		8	2
Exp Traffic/phone		0.15	>> (binom 8 1)
Number nodes		100	V
Exp Traffic / node		0.30	
Oper min/yr		91980	45990
Break-even cost	$	0.1093	

		VSATs		Hub
Unit Price	$	(11,250)	$	(150,000)
Installation cost	$	(1,000)	$	(10,000)
Unit Lease	$	-	$	-
Maintenance	$	(360)	$	(100,000)
BW ($/carrier)	$	(5,500)	$	(550,000)
Fees / Licensing	$	(100)	$	(5,000)
PSTN access fee	$	(0.04)	$	-
Capital costs	$	(1,235,000)	$	(165,000)

Lifecycle economic analysis

Year	VSAT Var cost	Hub Var cost	Total costs	Revenue/yr	Profits	
1	($1,321,840)	($650,000)	$3,371,840	$2,010,627	($1,361,213)	
2	($2,442,043)	($1,200,847)	$3,642,891	$3,714,549	($1,289,555)	
3	($3,391,368)	($1,667,667)	$5,059,036	$5,158,550	($1,190,041)	
4	($4,195,881)	($2,063,277)	$6,259,158	$6,382,280	($1,066,919)	
5	($4,877,671)	($2,398,540)	$7,276,211	$7,419,339	($923,792)	
6	($5,455,460)	($2,682,661)	$8,138,121	$8,298,203	($763,710)	
7	($5,945,111)	($2,923,442)	$8,868,553	$9,043,002	($589,261)	
8	($6,360,070)	($3,127,493)	$9,487,563	$9,674,189	($402,635)	
9	($6,711,730)	($3,300,418)	$10,012,147	$10,209,092	($205,690)	<--- Table pivot
10	($7,009,746)	($3,446,964)	$10,456,711	$10,662,400	$0	

Fixed MCPC
Economic Model

50% more on VSAT, Hub cost

23.8% of the time only
2 users pay BW

nodes	Projected traffic intensity (Erlangs)					
$0	**0.025**	**0.05**	**0.10**	**0.20**	**0.25**	**0.33**
20	($9,204,527)	($8,437,650)	($6,903,898)	($3,836,392)	($2,302,639)	$243,390
50	($20,472,214)	($18,555,023)	($14,720,641)	($7,051,877)	($3,217,495)	$3,147,579
100	($42,178,201)	($38,343,820)	($30,675,056)	($15,337,528)	($7,668,764)	$5,061,384
200	($88,522,722)	($80,853,958)	($65,516,430)	($34,841,374)	($19,503,847)	$5,956,450
500	($203,959,029)	($184,787,120)	($146,443,300)	($69,755,661)	($31,411,841)	$32,238,899

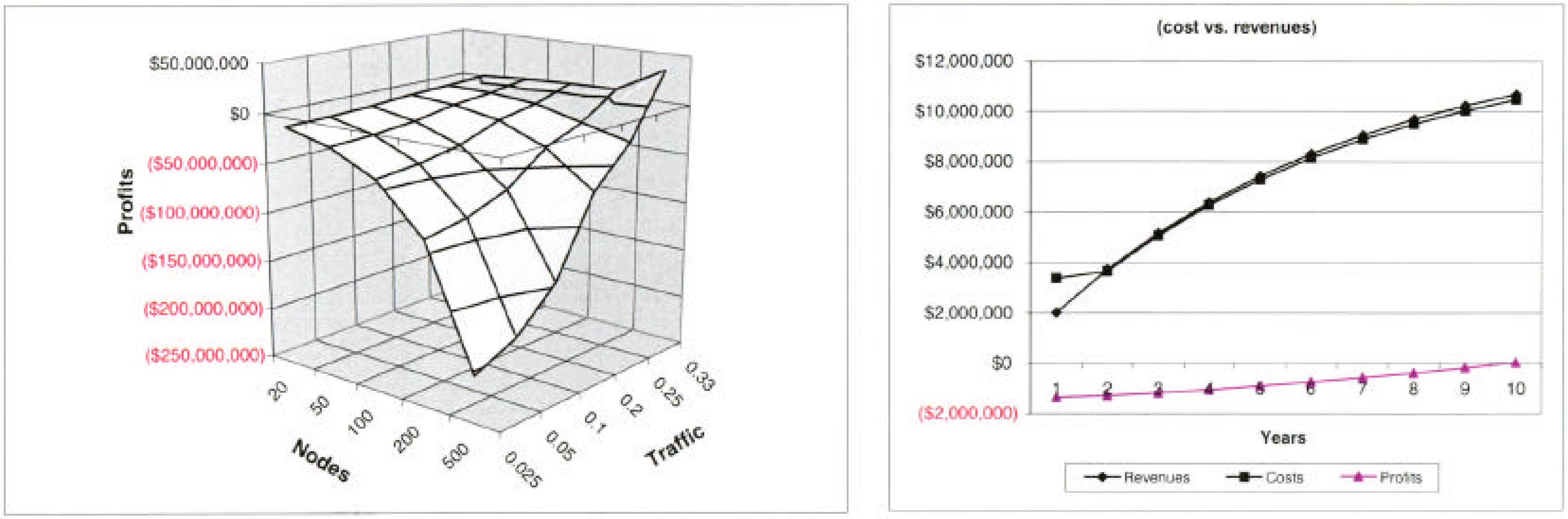


Figure 5.4 Fixed MCPC simulation results for two TDM voice channels per VSAT

Figure 5.5 shows that the increase in the number of network nodes does not have a significant impact on the user cost, but rather that the actual number of simultaneous users is the reason for the decrease in cost.

5.1.2.3 High Traffic Scenario

Figures 5.3 and 5.4 show the different effects of high traffic on overall economic planning, again depending upon the number of simultaneous TDM channels. Although the user traffic intensity is the same, Figure 5.3 with only one-user shows smaller revenue although the total profit is actually much larger.

There are some interesting conclusions when comparing Figures 5.3 and 5.4, both relating to the Fixed MCPC model. While the one-voice channel analysis in Figure 5.3 shows a high traffic (0.25 Erlang) profit range from $5 million (20 nodes) to $160 million (500 nodes), the two-voice channel from Figure 5.4 is still generating losses, ranging from $2 million (20 nodes) to $31 million (500 nodes). The two-voice channel only generates profits when traffic is above 0.30 Erlangs.

From the same 3-D plot in Figure 5.3 it is possible to see the projected earnings for a larger-than-expected user traffic behavior, both in terms of network size as well as in terms of expected traffic intensity. The extreme behavior of the single voice channel MCPC model is unusual, since the profit curve for a large network with high traffic is almost exponential at some points.

Figure 5.6 shows the comparison of the profit earning curves for low, medium and high traffic analysis for single voice channel per VSAT, while Figure 5.7 shows the same information for the two voice channel earth station. It can be seen that the relative VSAT capital cost is reduced while the VSAT variable cost increases in almost the same proportion.

Figures 5.6 and 5.7 also show pie charts for low, medium and high traffic scenarios for a Fixed-MCPC satellite network during its first year of operation, where the VSAT capital investment clearly dominates over the hub capital cost.

The VSAT segment also generates more expenses in the variable costs, mainly due to the PSTN access fee for each user voice channel, as it can be appreciated in Figure 5.7. It is also easy to see how by increasing the number of calls, or traffic, the variable costs of the

No. VSATs	20	50	100	200	500
No. users	$/min call	$/min call	$/min call	$/min call	$/min call
1	$0.4705	$0.4260	$0.4350	$0.4526	$0.4208
2	$0.2453	$0.2230	$0.2275	$0.2363	$0.2204
3	$0.1702	$0.1553	$0.1583	$0.1642	$0.1536
4	$0.1326	$0.1215	$0.1237	$0.1261	$0.1202
5	$0.1101	$0.1012	$0.1030	$0.1065	$0.1002
6	$0.0951	$0.0877	$0.0892	$0.0921	$0.0868
7	$0.0844	$0.0780	$0.0793	$0.0818	$0.0773
8	$0.0763	$0.0707	$0.0719	$0.0741	$0.0701

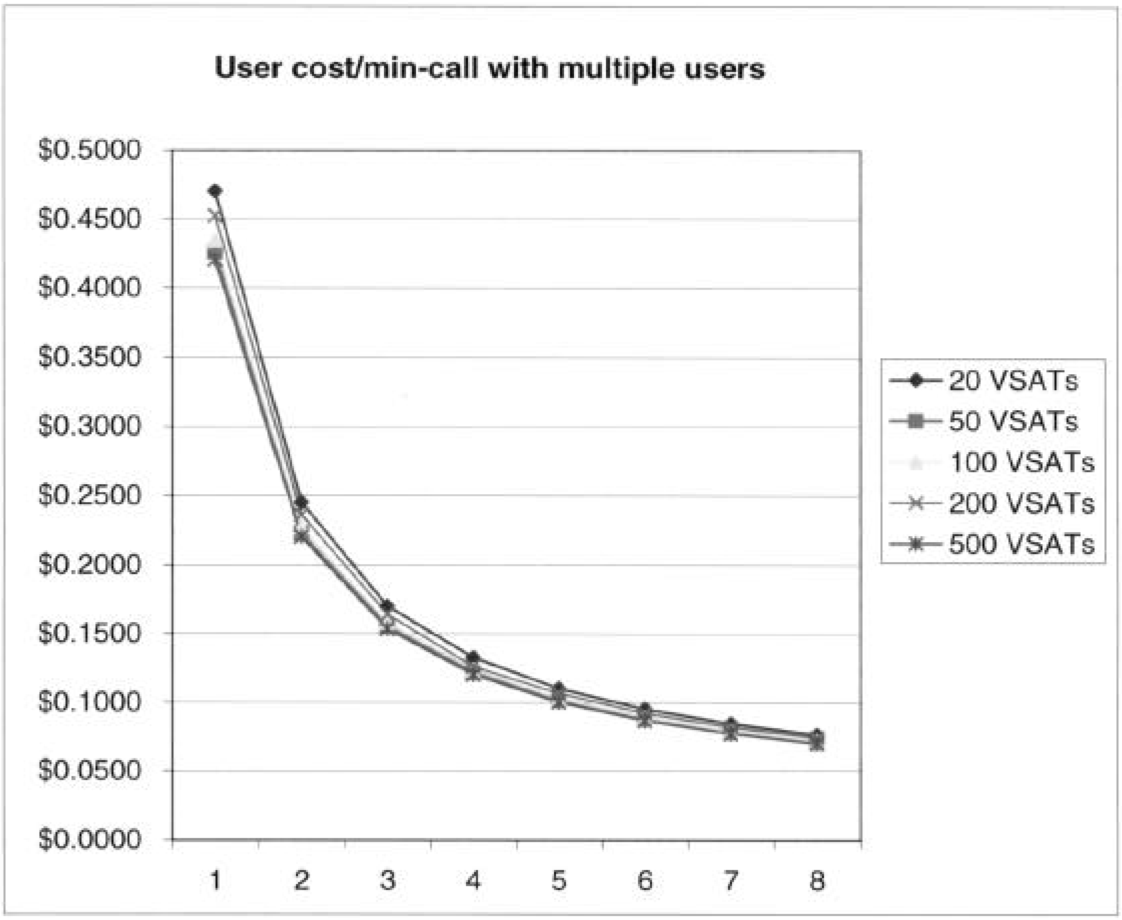


Figure 5.5 Variation of user cost with multiple TDM users for Fixed MCPC

Fixed MCPC model

Projected traffic	User cost	0.025	0.05	0.10	0.20	0.25	0.33	VSAT capital	Hub capital	VSAT var	Hub var
Low Traffic	$0.8716	($23,006,292)	$0	$46,012,583	$138,037,750	$184,050,334	$260,431,222	($1,235,000.00)	($165,000.00)	($647,320.00)	($650,000.00)
Medium traffic	$0.3172	($38,343,820)	($30,675,056)	($15,337,528)	$15,337,528	$30,675,056	$56,135,352	($1,235,000.00)	($165,000.00)	($769,960.00)	($650,000.00)
High traffic	$0.2063	($41,411,325)	($36,810,067)	($27,607,550)	($9,202,517)	$0	$15,276,178	($1,235,000.00)	($165,000.00)	($892,600.00)	($650,000.00)

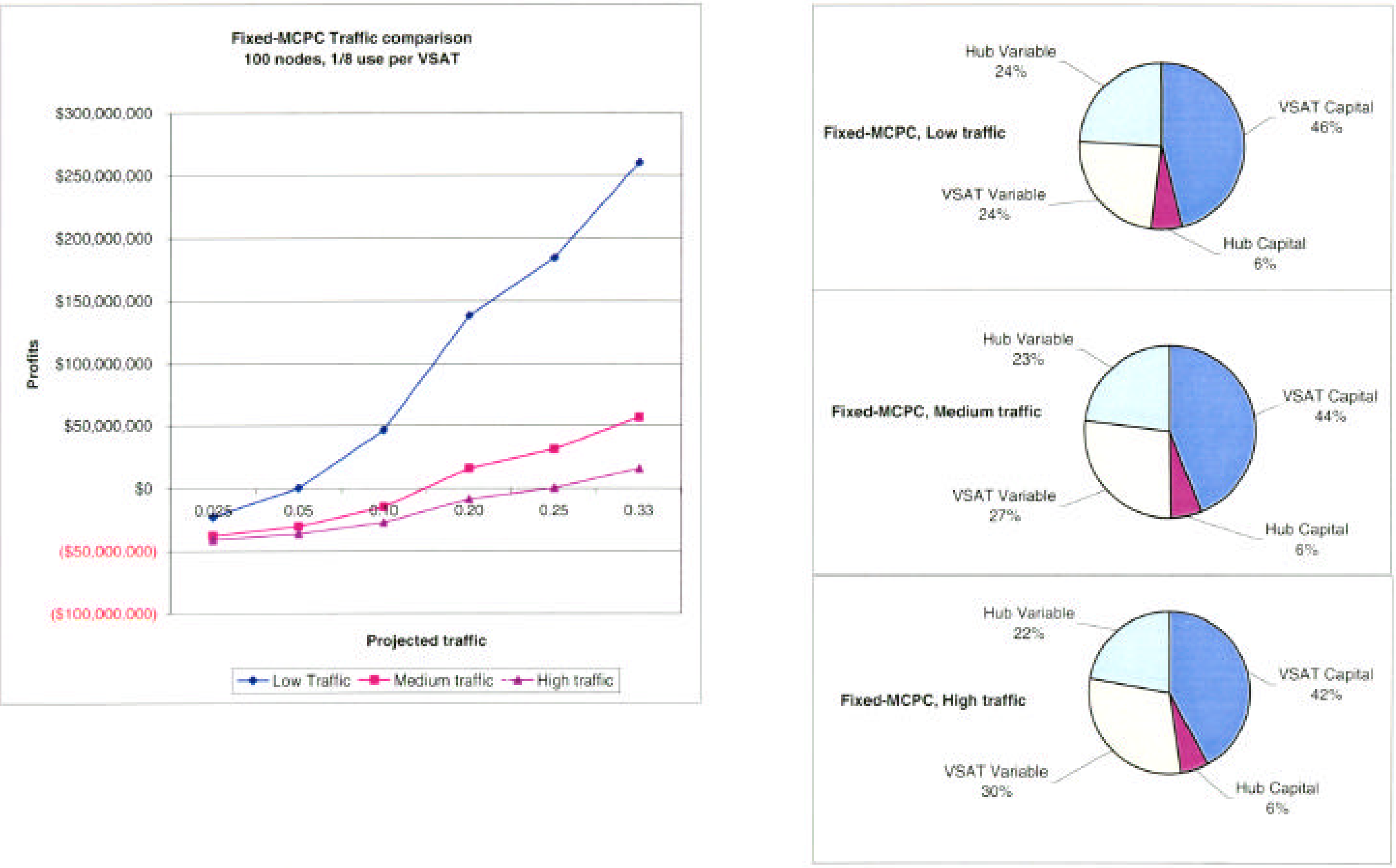


Figure 5.6 Comparison of low, medium and high traffic for single user MCPC

Fixed MCPC model (2 voice channels/VSAT)

Projected traffic	User cost	0.025	0.05	0.10	0.20	0.25	0.33	VSAT capital	Hub capital	VSAT var	Hub var
Low Traffic	$0.2479	($34,509,438)	($23,006,292)	$0	$46,012,583	$69,018,875	$107,209,319	($1,235,000)	($165,000)	($831,280)	($650,000)
Medium traffic	$0.1093	($42,178,201)	($38,343,820)	($30,675,056)	($15,337,528)	($7,668,764)	$5,061,384	($1,235,000)	($165,000)	($1,076,560)	($650,000)
High traffic	$0.0816	($43,711,954)	($41,411,325)	($36,810,067)	($27,607,550)	($23,006,292)	($15,368,203)	($1,235,000)	($165,000)	($1,812,400)	($650,000)

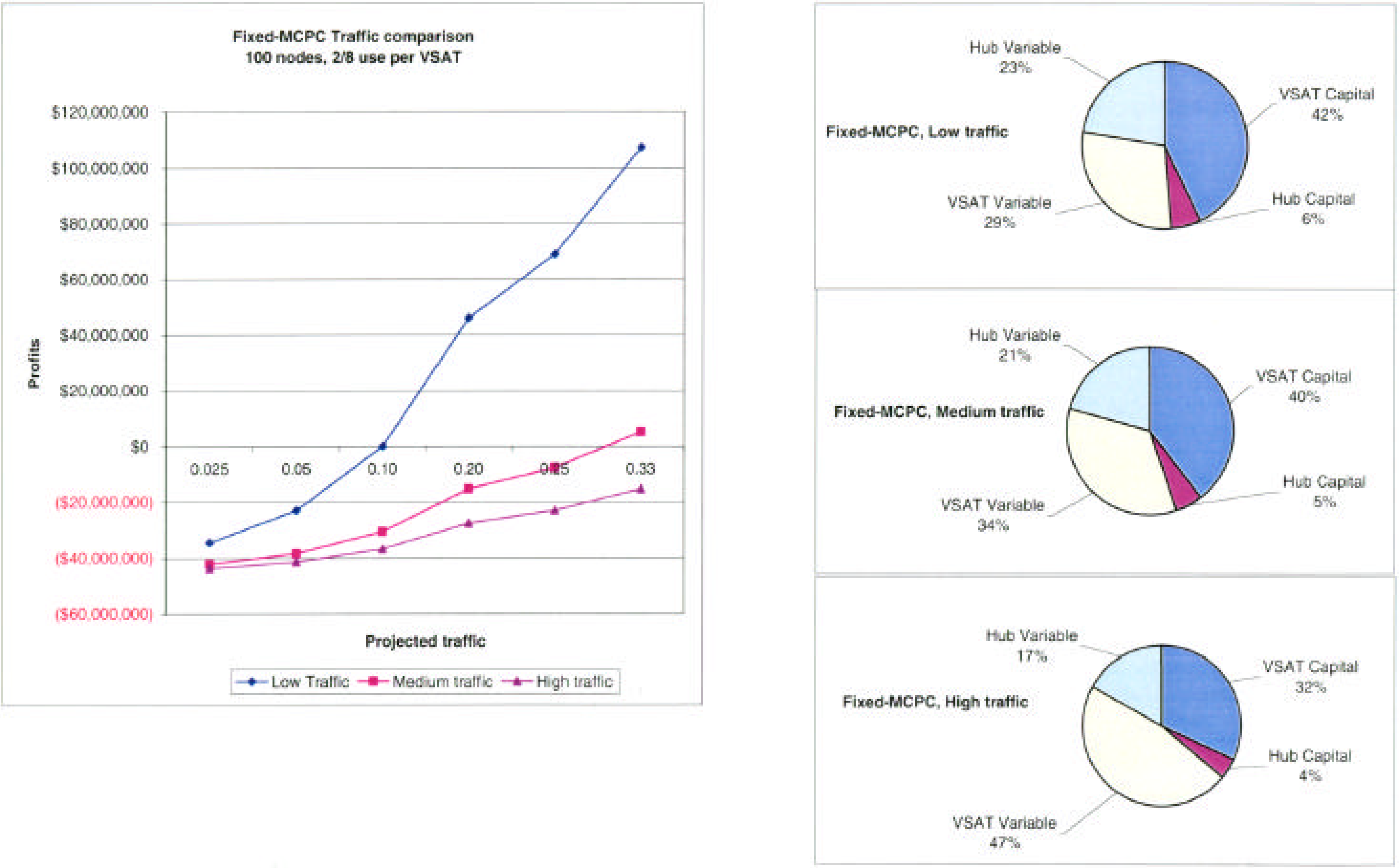


Figure 5.7 Comparison of low, medium and high traffic for two-user MCPC model

VSAT segment particularly increase due to the satellite and connection fees for a larger number of terminals.

It is possible to conclude that in Fixed-MCPC network satellite analysis, network size defines the general cost of the network and that the network's operation is expensive. It also is safe to conclude that a reduced number of TDM users per earth station define the economic performance of the network.

Fixed-MCPC networks does not produce profits if traffic is low, but may generate dramatic loses or profits in large networks. A careful traffic analysis for Fixed MCPC must be made, considering different network sizes, varying traffic and especially the statistic for second or third users in TDM channels

5.1.3 SCPC DAMA Model

This Section presents the parametric analysis results of the SCPC DAMA economic model for a low traffic (pessimistic), a medium traffic (nominal) and a high traffic (optimistic) scenario, with changing projections in each case.

The basic SCPC DAMA scenario is shown in Figure 5.8, along with its data tables and performance graphs. The network is composed of 100 nodes and 25 satellite carriers that allow for 1.8 % GoS with a traffic intensity of 0.15 Erlang per user. It is easily seen that the smaller amount of carriers with respect to the number of nodes allows for an improvement in expenditures in this network. The quality of the network is expressed in the 1.8 % GoS. Although the network may use only a small number of earth stations at any given moment, an SCPC DAMA network usually requires a large capital outlay to start operations. Although the hub is important, and it may be a major expense, it is the least expensive part of the network. A large part of the varying network expenses are caused both by maintenance to the earth stations (whether they are being used or not) and to pay for the satellite channels and connection time to the PSTN.

The lifetime economic analysis shows the network reaching the break-even point at the end of the tenth year, allowing investors to obtain their expected return on investment. The 3-Dimensional (3-D) plot shown in Figure 5.8 shows the Profits-vs.-Nodes-vs.-Traffic projections of the network for other values of traffic intensity and network size, obtained from the table pivot value at the right bottom of the lifetime cost table.

SCPC DAMA
Economic Model

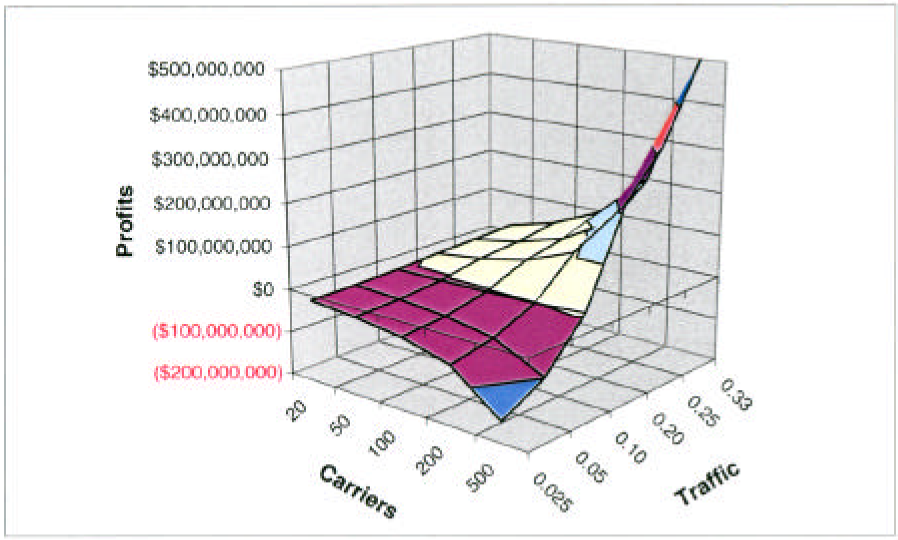
Interest Rate	18%
Total # nodes **N**	100
Grade of Service	1.8%
No. RF carriers **n**	25
Exp. Sat. Traffic	0.15
No. oper min/yr	45990
Break-even cost	$0.4210

	VSATs	Hub
Unit Price	$ (7,500)	$ (100,000)
Installation cost	$ (1,000)	$ -
Unit Lease	$ -	$ -
Maintenance	$ (360)	$ (100,000)
BW ($/carrier)	$ (5,500)	$ (137,500)
Fees / Licensing	$ (100)	$ (15,000)
PSTN access fee	$ (0.04)	$ -
Fixed costs	$ (860,000)	$ (115,000)

	Lifecycle economic analysis				
Year	VSAT Var cost	Hub Var cost	Total costs	Revenue/yr	Profits
1	($219,490)	($237,500)	$1,431,990	$484,003	($947,987)
2	($405,498)	($438,771)	$844,270	$894,174	($898,083)
3	($563,133)	($609,340)	$1,172,473	$1,241,777	($828,778)
4	($696,721)	($753,890)	$1,450,611	$1,536,356	($743,033)
5	($809,932)	($876,390)	$1,686,321	$1,785,999	($643,355)
6	($905,873)	($980,203)	$1,886,076	$1,997,561	($531,870)
7	($987,179)	($1,068,181)	$2,055,359	$2,176,851	($410,378)
8	($1,056,082)	($1,142,738)	$2,198,820	$2,326,792	($280,406)
9	($1,114,475)	($1,205,922)	$2,320,397	$2,457,555	($143,248)
10	($1,163,960)	($1,259,468)	$2,423,428	$2,566,676	$0

<--- Table pivot

Nodes	Projected traffic intensity (Erlangs)					
$0	0.025	0.05	0.10	0.20	0.25	0.33
20	($11,716,610)	($9,608,641)	($5,392,703)	$3,039,172	$7,255,110	$14,278,862
50	($20,465,783)	($15,195,861)	($4,656,017)	$16,423,673	$26,963,517	$44,522,898
100	($35,047,739)	($24,507,894)	($3,428,205)	$38,731,173	$59,810,862	$94,929,624
200	($64,211,650)	($43,131,961)	($972,583)	$83,346,174	$125,505,552	$195,743,076
500	($151,703,383)	($99,004,160)	$6,394,286	$217,191,177	$322,589,622	$498,183,432



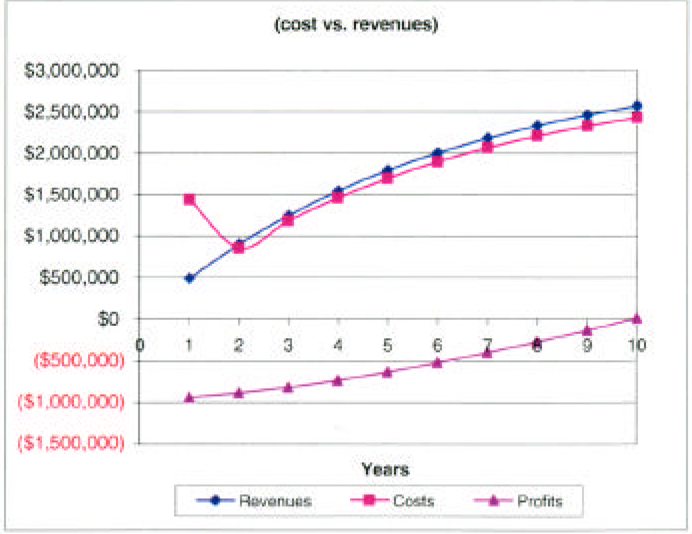


Figure 5.8 SCPC DAMA simulation results for VSAT network design

5.1.3.1 Low Traffic Scenario

The SCPC DAMA network is designed especially for applications with a large number of network nodes and a small number of users actually on the network at any given time. The main idea in SCPC DAMA is to optimize the satellite resource by assigning channels by demand only. Nevertheless, a small network will hardly be economically autonomous if the traffic demand is small compared to the capacity of the network. In the analysis, a 100 node network was assumed, with 25 satellite carriers and an expected low user traffic intensity of 0.05 Erlang. Figure 5.8 shows the low traffic performance of the simulated network, along with its economic implications.

In a low traffic scenario, and due to the large investment created when implementing a SCPC DAMA, this network shows the largest economic component to the VSAT portion (all remotes in the network). In very low traffic situations, earning would not recover the investment, with the possibility of losing $9 million on a small network, and up to $99 million in a large network, for 0.05 Erlangs traffic. The loss is larger for even lower traffic figures like the 0.025 Erlang projection shown in the table.

Figure 5.9 shows the relative impact of low traffic in projections. The low traffic plot on the graph shows a markedly positive profit for projections based on the low traffic assumption. This behavior may be misleading, since the projection upon which the curve is based assumes the user cost at $1.18/min of service. That is the value that the model found suitable to make the low traffic scenario able to meet the end of lifetime break-even point. That figure is definitively not representative of the reality of rural telephony; therefore the low traffic assumption in an SCPC DAMA scenario will hardly make any profit. On the same Figure 5.9, the pie chart for low-traffic, first-year expenses shows that the VSAT capital investment clearly dominates costs, as often happens in an SCPC DAMA network.

5.1.3.2 Medium Traffic Scenario

In a medium traffic (optimal) situation, an SCPC DAMA network performs as expected regarding the cost and revenue performance due to traffic. The network size is not relevant to the general profitability of the network, since it depends rather upon traffic, but a larger network does generate a larger revenue for the same assumed traffic.

SCPC DAMA model

Projected traffic	User cost	0.025	0.05	0.10	0.20	0.25	0.33	VSAT capital	Hub capital	VSAT var	Hub var
Low Traffic	$1.1829	($13,968,050)	$17,651,484	$80,890,551	$207,368,686	$270,607,753	$375,964,039	($860,000)	($115,000)	($188,830)	($237,500)
Medium traffic	$0.4210	($35,047,739)	($24,507,894)	($3,428,205)	$38,731,173	$59,810,862	$94,929,624	($860,000)	($115,000)	($219,490)	($237,500)
High traffic	$0.2686	($39,263,677)	($32,939,770)	($20,291,957)	$5,003,670	$17,651,484	$38,722,741	($860,000)	($115,000)	($250,150)	($237,500)

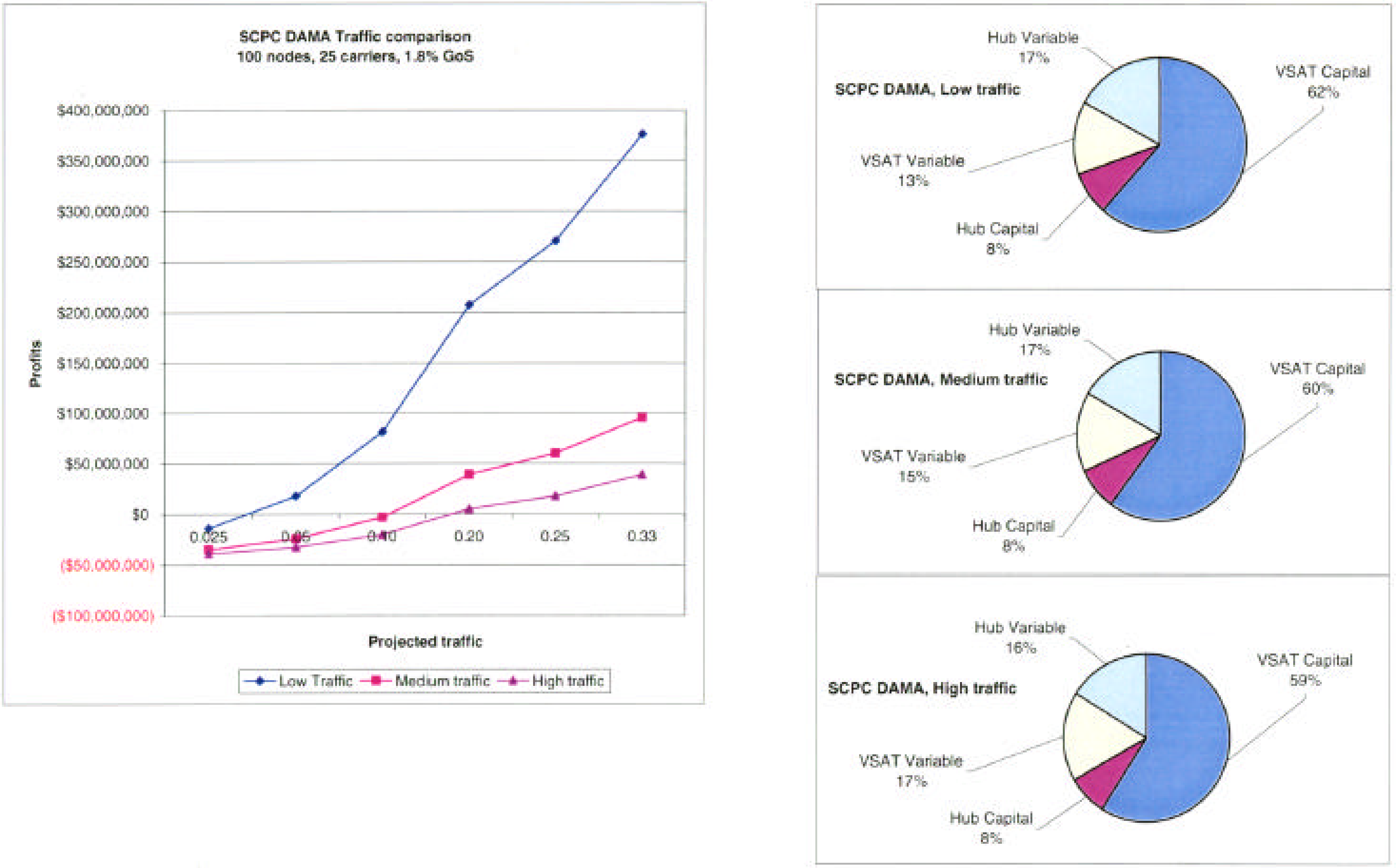


Figure 5.9 Comparison of low, medium and high traffic for the SCPC DAMA model

As mentioned before, the number of operating earth stations is directly related to the traffic analysis that defined the number of satellite carriers, and small traffic variations do not disrupt the expected performance of the network. An interesting point is the fact that larger networks provide larger revenue without large operating expenses, especially due to lower satellite capacity and PSTN access expenses.

The 3-D plot shown in Figure 5.8 shows that medium traffic is around the break-even point in practically all network size projections. This means that the user cost figure found during the optimization process, $0.42/min, is probably a safe parameter to assume for this type of network given the other parameters as valid (fixed and variable VSAT and hub costs). On the other hand, what is projected in Figure 5.8 is the actual number of satellite carriers, which is the parameter that creates expenses and generates revenue. The total number of nodes, or earth stations, is independent of the number of carriers, except for their relationship to obtain the desired Grade of Service.

Figure 5.9 shows the predominance of the VSAT overall cost in the first year of operations (pie charts), with a small variation in the medium traffic scenario for VSAT capital (lower) and variable (higher) relative costs compared to the lower traffic scenario. This implies that when traffic increases the operational costs (satellite capacity, PSTN access) also increase as a direct function of traffic.

5.1.3.3 High Traffic Scenario

The high traffic scenario for an SCPC DAMA network is based upon the assumption that every carrier is used to its highest possible number of minutes per year, therefore generating lower expenses and more revenue than fixed-assignment networks.

As the 3-D plot on Figure 9.8 shows, all high traffic projections show a substantial amount of profits, especially over a large network with many carriers. This is simply a direct result of the user cost obtained for the break-even analysis and model implementation. The projections shown were based upon the medium traffic 0.15 Erlangs case and projected over a larger number of carriers. The higher traffic scenario figures, shown in the table at the top of Figure 5.9, shows a more modest profit due to the lower user cost figure found at this scenario, in this case $0.27/min. The pie chart for the high traffic scenario of Figure 5.9 also show figure a small decrease in VSAT capital cost vs. a small increment on variable VSAT cost.

5.1.4 Mesh SCPC-DAMA Model

As described in Section 4.4.3.4, the Mesh SCPC DAMA model is based on a number of earth stations N which can connect to each other, and use a number of gateways, or mini-hubs, to interconnect to the PSTN. It is assumed that each gateway can support up to n carriers, so the total number of satellite carriers at any moment is $n \times g$, which is the figure taken as the number of nodes communicating through the satellite network.

For the analysis presented in this research, a number of four gateways was used, with each gateway providing a capacity of 25 satellite carriers from 100 earth stations. What this means is that, although each earth station can communicate with any other each other as in any mesh network, those requiring an outlet to the PSTN may do so through any of the gateways. Any user has an associated expected traffic, which is used to project variations in traffic and number of nodes.

5.1.4.1 Low Traffic Scenario

In the Mesh SCPC DAMA scenario, as it has been in all other models for low traffic scenarios, the main characteristic is the high amount of profits that are projected by the models. Figure 5.10 shows the impressive amount of profits generated by the Mesh SCPC DAMA model when projected for large size networks.

Again, the main reason behind this behavior is a result of the optimization process when setting the break-even point for low traffic, reached at the end of the system's lifetime. For low traffic applications, this can only be accomplished when a large user cost tariff is imposed. In this case, for mesh SCPC DAMA the user cost is \$1.82/min, which is obviously impractical for rural telephony applications, but is very attractive for investors looking for revenue and for large profit numbers.

In fact, the projection for large network size when using the low traffic scenario turns out to be over \$560 million above the break-even point, as shown in Figure 5.11. An important piece of information is shown in the pie chart for low traffic at Figure 5.11, where it is easy to see the large proportion of capital investment required for the mesh SCPC DAMA model presented here. The cost of the hubs is larger than that of the combined VSATs, since each mini-hub must be able to handle a large number of calls.

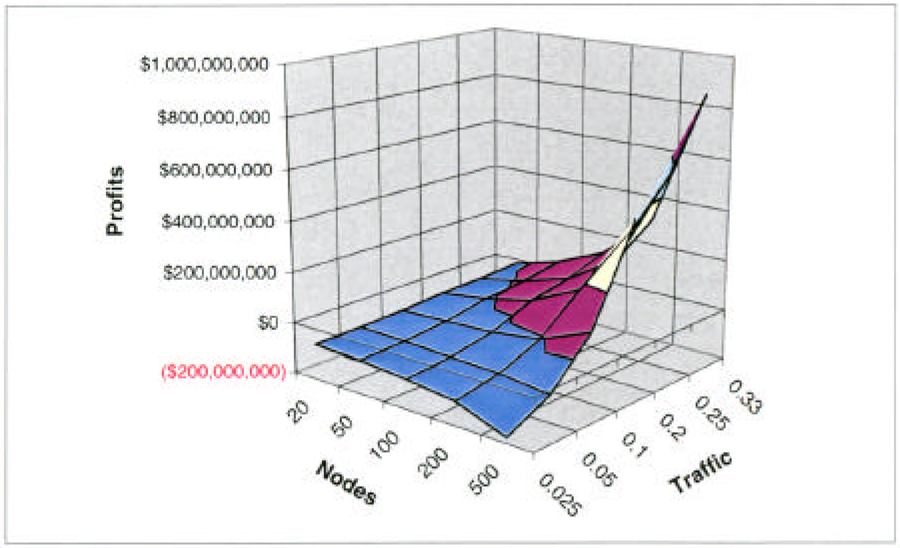
Mesh SCPC DAMA
Economic Model

Interest Rate	18%	
	Gateways	Network
No. Gateways	4	
Carrier/Gateway	25	100
Number nodes	100	400
Exp Traffic / node	0.15	
Oper min/yr	45990	
Break-even cost	$ 0.6361	

	VSATs	Gateways
Unit Price	$ (7,500)	$ (1,000,000)
Installation cost	$ (1,000)	$ (100,000)
Unit Lease	$ -	$ -
Maintenance	$ (360)	$ (320,000)
BW ($/carrier)	$ (5,500)	$ (550,000)
Fees / Licensing	$ (100)	$ (1,000)
PSTN access fee	$ (0.04)	$ -
Capital costs	$ (3,440,000)	$ (4,404,000)

	Lifecycle economic analysis				
Year	VSAT Var cost	Hub Var cost	Total costs	Revenue/yr	Profits
1	($877,960)	($1,830,000)	$10,551,960	$2,925,279	($7,626,681)
2	($1,621,994)	($3,380,847)	$5,002,841	$5,404,330	($7,225,192)
3	($2,252,531)	($4,695,125)	$6,947,656	$7,505,220	($6,667,628)
4	($2,786,885)	($5,808,919)	$8,595,804	$9,285,636	($5,977,797)
5	($3,239,727)	($6,752,813)	$9,992,540	$10,794,462	($5,175,874)
6	($3,623,491)	($7,552,723)	$11,176,214	$12,073,129	($4,278,959)
7	($3,948,715)	($8,230,613)	$12,179,328	$13,156,745	($3,301,543)
8	($4,224,329)	($8,805,095)	$13,029,424	$14,075,063	($2,255,904)
9	($4,457,900)	($9,291,945)	$13,749,845	$14,853,299	($1,152,450) <— Table pivot
10	($4,655,841)	($9,704,530)	$14,360,371	$15,512,821	$0

nodes	Projected traffic intensity (Erlangs)					
$0	0.025	0.05	0.10	0.20	0.25	0.33
20	($60,044,865)	($56,746,663)	($50,150,258)	($36,957,448)	($30,361,043)	($19,411,011)
50	($67,248,688)	($59,003,182)	($42,512,170)	($9,530,146)	$6,960,866	$34,335,946
100	($82,455,060)	($65,964,048)	($32,982,024)	$32,982,024	$65,964,048	$120,714,207
200	($105,667,803)	($72,685,779)	($6,721,732)	$125,206,364	$191,170,412	$300,670,731
500	($175,306,034)	($92,850,974)	$72,059,145	$401,879,384	$566,789,504	$840,540,302



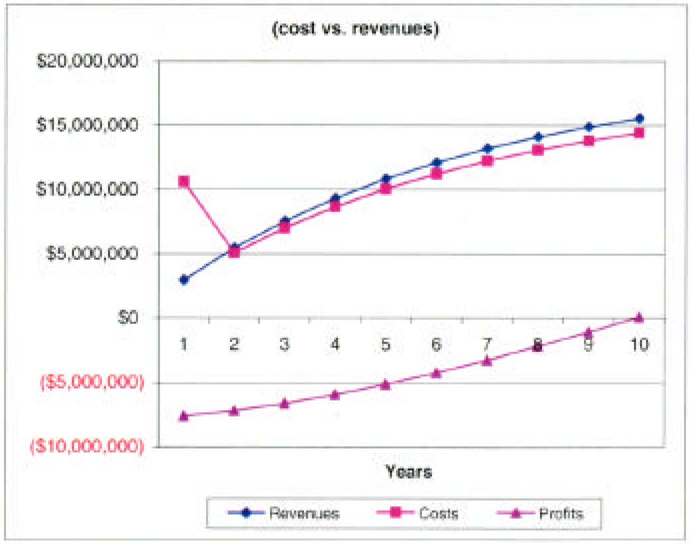


Figure 5.10 Mesh SCPC DAMA simulation results for VSAT network design

Mesh SCPC DAMA model

Projected traffic	User cost	0.025	0.05	0.10	0.20	0.25	0.33	VSAT capital	Hub capital	VSAT var	Hub var
Low Traffic	$1.8282	($49,473,036)	$0	$98,946,072	$296,838,215	$395,784,287	$560,034,766	($3,440,000)	($4,404,000)	($755,320)	($1,830,000)
Medium traffic	$0.6361	($82,455,060)	($65,964,048)	($32,982,024)	$32,982,024	$65,964,048	$120,714,207	($3,440,000)	($4,404,000)	($877,960)	($1,830,000)
High traffic	$0.3976	($89,051,465)	($79,156,857)	($59,367,643)	($19,789,214)	$0	$32,850,096	($3,440,000)	($4,404,000)	($1,000,600)	($1,830,000)

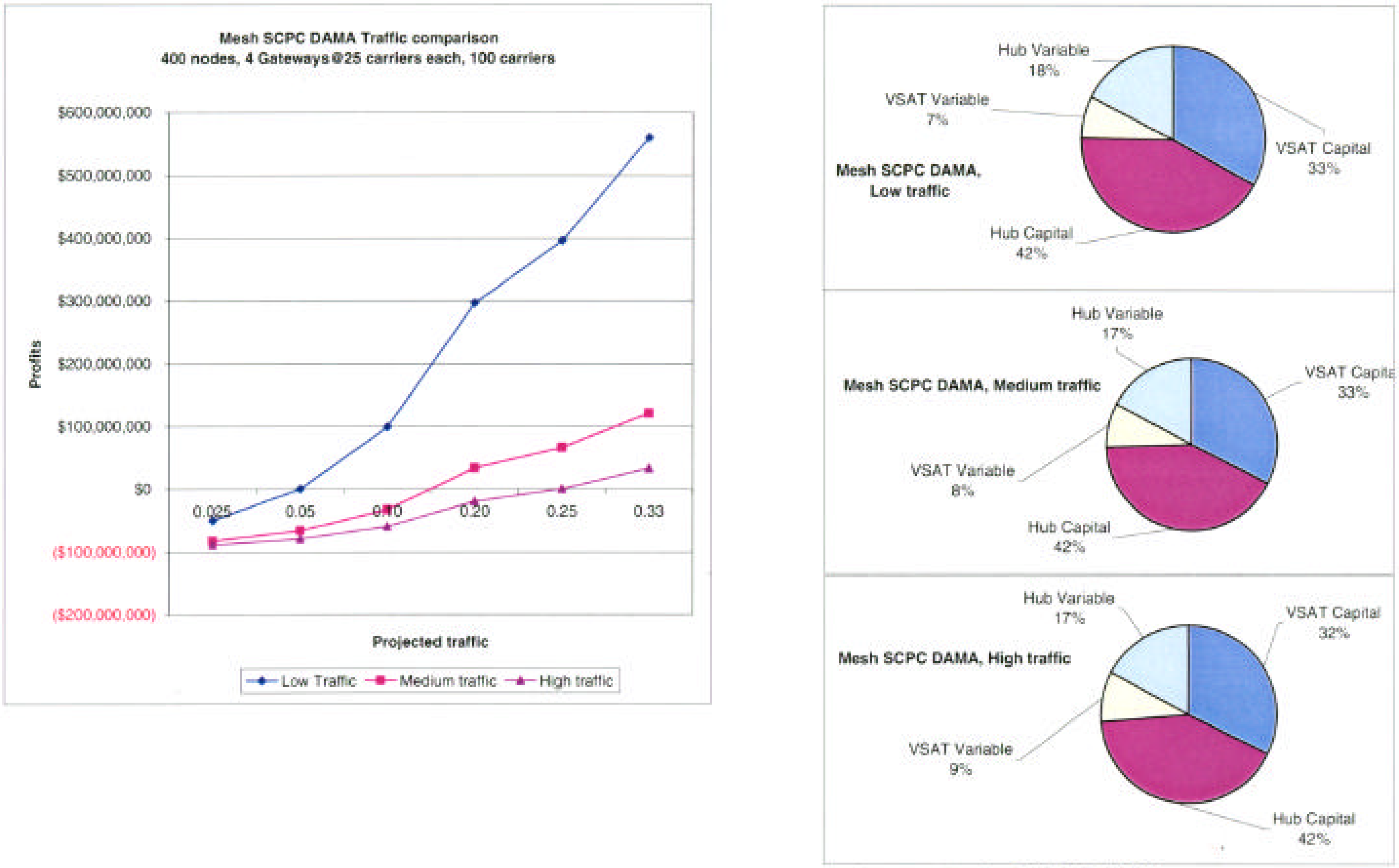


Figure 5.11 Low, medium and high traffic comparisons for the Mesh SCPC DAMA model

5.1.4.2 Medium Traffic Scenario

A more conservative, and more realistic, idea of the network's performance regarding traffic and profits can be derived from the 3-D plot on Figure 5.10. This plot actually corresponds to the medium traffic scenario, and it can be seen that the profitable performance for the medium traffic scenario (0.15 Erlangs) is found above 0.15 Erlangs of traffic, and for networks with more than 50 satellite carriers.

A user cost of $0.63/min is still considered high, but closer to the expected value of $0.25 to $0.40 per minute expressed as desirable in Chapter 4. Figure 5.11 also shows how the medium traffic analysis can be projected over a larger network with a large number of carriers, providing considerable earnings (around $120 million) but not quite as much as the low traffic projections ($560 millions).

5.1.4.3 High Traffic Scenario

The high traffic scenario provides the best user cost value of all Mesh SCPC DAMA scenarios, optimizing the network to a $0.39/min user cost. Although the revenue projections for this value are not as attractive as the previous scenarios, the high traffic projections allow for a very solid and feasible network implementation. It also provides the lowest user cost, in this case, $0.39/min, which is inside the allowed range of price for the network.

Although the 3-D plot in Figure 5.10 shows the projection to grow rapidly along with the network size, in reality any mesh network must have a medium to large traffic intensity to actually be profitable. This is needed due to the large initial investment caused by the VSATs and Hub capital cost.

Although the user cost is lower than the other mesh scenarios and thus the profits are lower, the lower user cost will probably attract more users, thus having the positive effect of increasing traffic. This way, in an indirect manner, revenue is increased by the higher traffic, thus increasing profits over a longer time. This model scenario allows a network designer to preview the network performance and decide which parameter needs to be changed or improved to further optimize the design.

5.2 Comparison of Multiple Access Models

The analysis of the different traffic intensity scenarios allow for a better understanding of the way the variables interact with each other during network operation. Each model has a different impact on the variables, and break-even points need to be found between their values in order to identify an improvement or decline of the network's performance beyond some equilibrium point.

Probably the three most important parameters for satellite rural telephone network design are network size, expected traffic capacity and user cost. Network size implies how many sites are serviced by the network in terms of required or available earth stations. Expected traffic capacity involves how often the telephone links are going to be used and how often service will be denied to incoming calls due to congestion. Finally, the user cost parameter involves how much the user has to pay to benefit from the service, if available.

This section provides a comparison and discussion about the interrelation between parameters in the same model, and among other models.

5.2.1 Effects Due to Traffic Intensity Variations

Traffic intensity patterns are unique to each economic, cultural, societal and geographical situation regarding telephone service habits. What could be an excuse for someone to make a telephone call would require an emergency for someone else to make the call.

If trying to obtain traffic behavior and habits for urban users is difficult, trying to establish the behavior of potential rural users is even more difficult, since there is no previous pattern of use. The few existing statistics regarding initial telephone usage in rural communities belong to the telephone companies, which do not like to share such information and treat it as confidential and proprietary.

Still, it is important to study the telephone traffic intensity variations and its performance effects on network planning and design, since it has been shown that there is a tremendous impact on both gains and loses. Although real-life figures are not easy to obtain, a number of estimated figures have been used in the model analyzes presented in this work.

One way to observe the expected traffic impact on profits is to run multiple parametric analyzes under different traffic values and observe the behavior of the different profit lines. As an example of this analysis, the Fixed SCPC model was analyzed searching for its sensitivity to variations on traffic and its impact on profits. The analysis based on 100 nodes with a constant user cost of $0.3142/min, which was optimized to break-even in 10 years at 0.15 Erlangs of traffic. In this analysis traffic was varied from 0.12 to 0.18 Erlangs in increments of 0.01 Erlang, and the resulting profit projections are plotted in Figure 5.12.

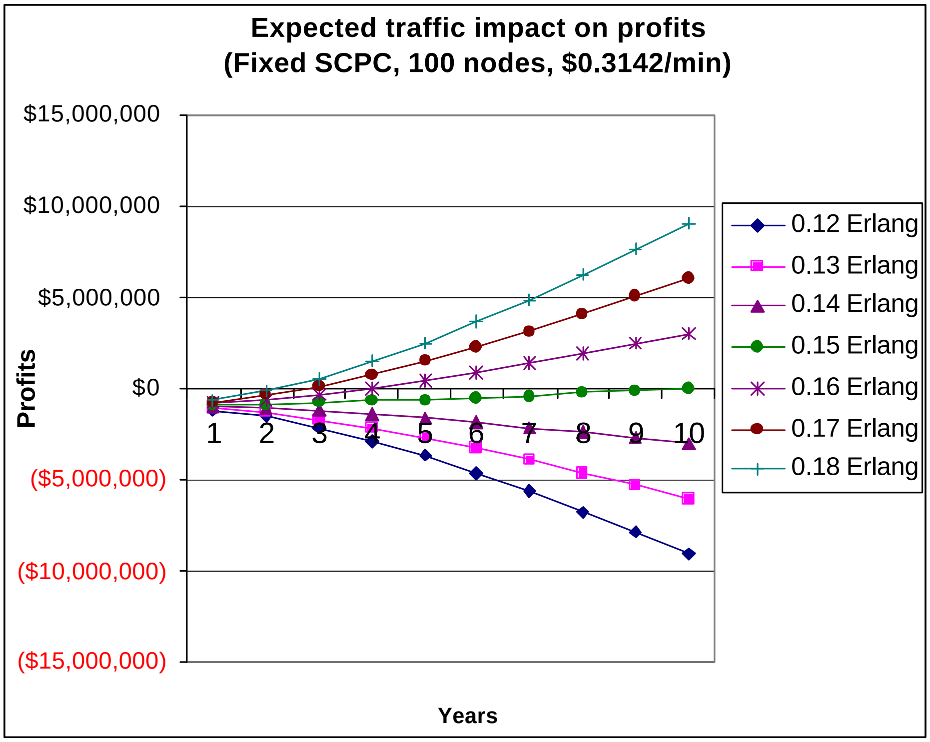
What this figure shows is the projection over the system's 10 year lifetime of the economic model behavior with varying traffic values for each case. It can be seen that break-even occurs at 0.15 Erlang, as originally designed. Curves with traffic density under that value increase the network losses to $9 million (0.12 Erlang), while curves over that value increase profits up to $9 million (0.18 Erlang). It can be shown that even a small change in either direction has an important impact on the network's economics.

As an example to demonstrate the magnitude of traffic change impact on profits, a variation of 0.01 Erlang, or 36 seconds in one hour, is applied over the 0.15 Erlang case used for medium traffic analysis. The change from 9 minutes per hour (0.15 Erlang) to 9 m 36 s (0.16 Erlang) in the expected traffic figure creates a surplus of $3,035,000. In the same token, a decrease of the same value to 8 m 24 s (0.14 Erlang) creates a deficit of the same amount.

Figure 5.12 shows how the relationship is linear, so a variation of 0.02 Erlang in either way will create an economic impact of twice that value ($6,070,000) in gains or losses, and 0.03 Erlang will change $9,105,000 either way. This is probably the main reason for which traffic studies need to be as precise as possible.

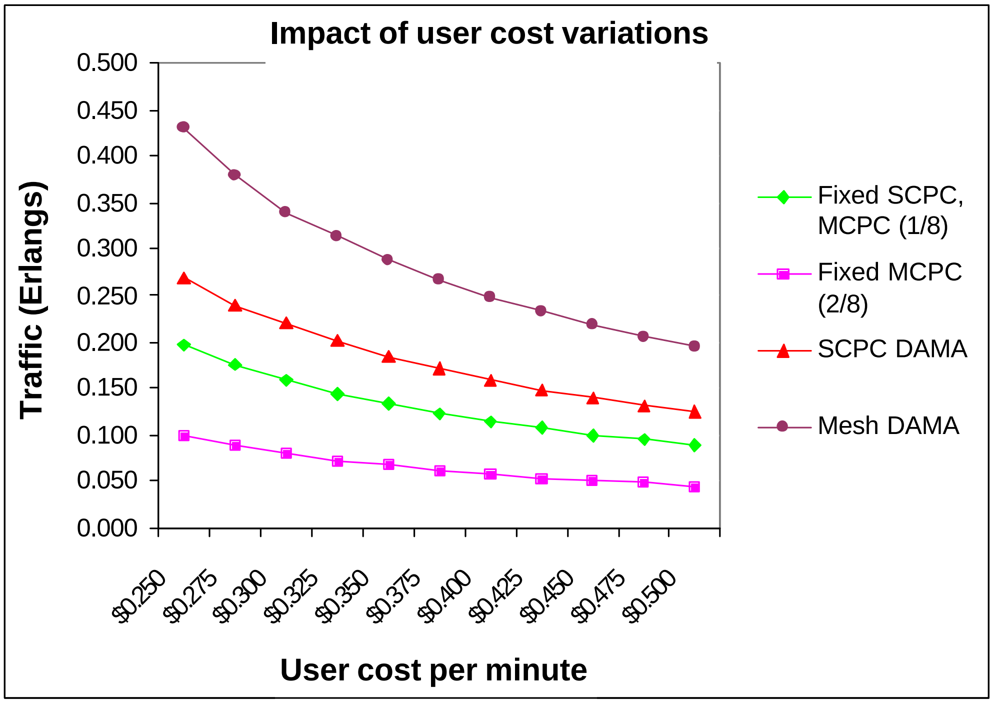
Another way to observe the effects of traffic intensity variations on network performance is to substitute the optimization variable. This is done by running a typical parametric analysis, then setting a pre-fixed parameter, such as user cost, and observing the sensitivity of the models by optimizing the traffic at different values. Figure 5.13 shows the impact on user cost per minute of each model according to the desired user cost ($0.25 to $0.50/min) for different traffic intensities.

Figure 5.12 Sensitivity of traffic changes on profits



Traffic (Er)	0.12	0.13	0.14	0.15	0.16	0.17	0.18
1	($1,141,920)	($1,057,830)	($973,740)	($889,000)	($805,000)	($721,000)	($637,000)
2	($1,561,145)	($1,321,702)	($1,082,259)	($842,000)	($603,000)	($363,000)	($124,000)
3	($2,143,340)	($1,688,152)	($1,232,964)	($777,000)	($322,000)	$132,000	$587,000
4	($2,863,645)	($2,141,533)	($1,419,000)	($697,000)	$24,000	$746,000	$1,469,000
5	($3,700,993)	($2,668,583)	($1,636,000)	($603,000)	$428,000	$1,461,000	$2,493,000
6	($4,637,530)	($3,258,066)	($1,878,000)	($499,000)	$880,000	$2,259,000	$3,639,000
7	($5,658,125)	($3,900,458)	($2,142,000)	($385,000)	$1,372,000	$3,130,000	$4,887,000
8	($6,749,956)	($4,587,687)	($2,425,000)	($263,000)	$1,899,000	$4,061,000	$6,223,000
9	($7,902,156)	($5,312,915)	($2,723,000)	($134,000)	$2,454,000	$5,044,000	$7,633,000
10	($9,105,517)	($6,070,344)	($3,035,000)	$0	$3,035,000	$6,070,000	$9,105,000

Figure 5.13 Impact of user cost per minute variations on required traffic



User cost	Resulting traffic intensity			
	F-SCPC	F-MCPC	DAMA	Mesh
$0.250	0.196	0.099	0.270	0.430
$0.275	0.175	0.088	0.240	0.380
$0.300	0.158	0.080	0.220	0.340
$0.325	0.144	0.073	0.201	0.314
$0.350	0.133	0.067	0.184	0.288
$0.375	0.123	0.062	0.171	0.267
$0.400	0.114	0.058	0.159	0.248
$0.425	0.107	0.054	0.148	0.232
$0.450	0.100	0.051	0.139	0.218
$0.475	0.095	0.048	0.131	0.206
$0.500	0.089	0.045	0.124	0.194

What Figure 5.13 shows is the required traffic per earth station that would bring user costs down to a reasonable (for rural purposes) economic level. This graph was obtained by setting the base user cost ($0.25 to $0.50/min) in increments of $0.025, or 2.5 cents, in an analysis based on 100 active nodes or satellite carriers. Setting the break-even point at 10 years, it allowed searching for the minimum traffic value that could provide such cost. The results are shown in Figure 5.13

It is easy to see that the most expensive technology for telephone service is the mesh SCPC DAMA model. This technology requires high user charges to recover the investment over the proposed system lifetime. Although the user cost is within the limits of the desired cost, it requires a very high traffic per node, even higher than this work terms "very high traffic", which is 0.33 Erlangs, for most rural telephone applications. The mesh technology, as simulated, would not last long under low, medium or even reasonably high traffic conditions, except perhaps by charging a high user cost.

The model for star SCPC DAMA offers the same user cost range as the mesh technology, but it has the advantage of requiring less traffic to reach the break-even point. This is good for a rural telephone network, since it means that it is easier to reach that investment return while providing a lower cost service to the user. Since SCPC DAMA is around the high to medium traffic region (0.25 to 0.15 Erlangs), the resulting user cost would still be in the upper half of the desirable cost region. This means that star SCPC DAMA can only offer a low user cost when high traffic is available, and must charge a higher user fee when lower traffic intensity is expected.

On the other hand, it can be seen that both fixed-assignment options (SCPC and MCPC) can offer the best service to users, since both can provide low user cost at low traffic rates. Especially interesting is the MCPC technology, which, under the worst case can transmit only one out of eight TDM channels (1/8), generating the same expenses and providing the same revenue as the single-channel SCPC. It is easily seen that the two-channel case (2/8) improves the service greatly, especially because it obtains twice the revenue with the same number of satellite channels.

It is easily seen that SCPC and MCPC (1/8) can provide the user with telephone service at low to medium traffic for a low user cost, while MCPC (2/8) provides the lowest user cost of them all. Logic indicates that more TDM channels in MCPC could reduce even more the tariff, but the probability of occurrence of (1/8) is 29% while that of (2/8) is only 5% of the time. More simultaneous users would increase revenue, but (3/8) is less than 0.5 percent of the time, so this is not a significant improvement.

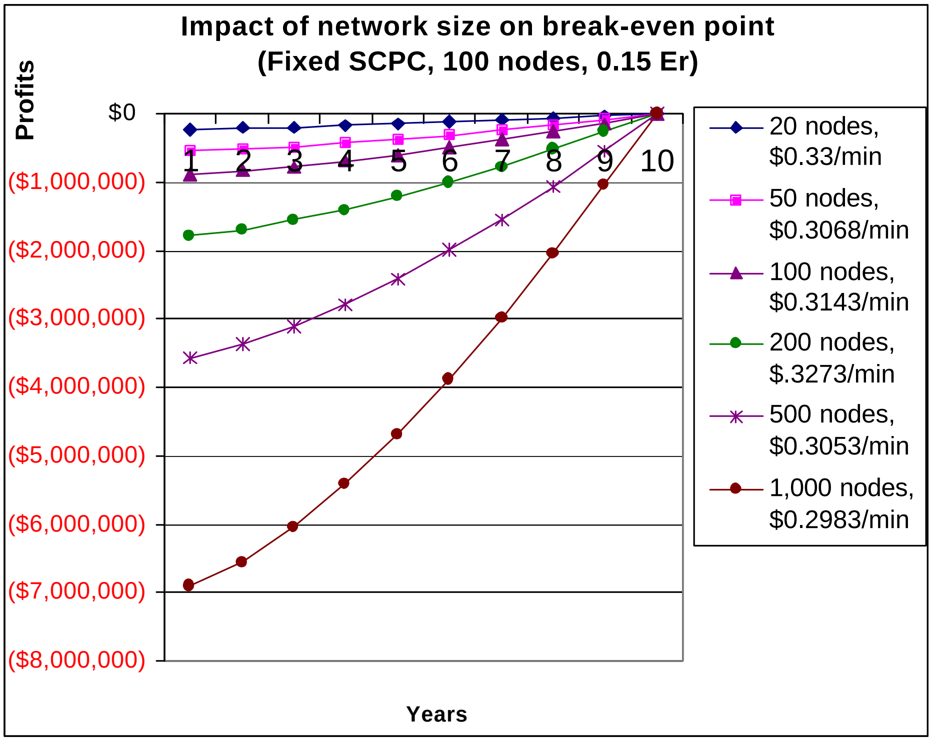
5.2.2 Effects Due to Network Size Variations

The network size, or total number of nodes also has an impact on the network design stage. It has been shown in Figures 5.1 through 5.12 how network size, along with traffic intensity, is probably the most important element to define when planning a satellite network. Although the direct impact of network size is important, the indirect effect that size has in optimizing revenue is more important, which then allows projection over large networks.

One possible way to measure the sensitivity of network size is by discussing the effect of size variations over the economic models. This means showing how variations of network size have an impact on profits. This is done by running successive analyzes over the economic model of any technology evaluated in this work. The analysis is done by setting the optimal break-even cost as pivot, and copying the column of profits (or losses) over the system's 10 years of lifetime. Once this is done, different network sizes are implemented on the models, including the user cost for each traffic scenario. Figure 5.14 shows how this information is used to compare the impact of varying network size into overall network profits.

What Figure 5.14 shows is the profit curve during the time it takes to reach the break-even point for different network sizes. At this point the initial revenue expectations are reached by the end of the system's lifetime. It can be seen how the smaller network (20 nodes) has 10 years to pay back little over $220,000. When the network grows to 50 earth stations, the amount to pay is over $544,000 in the same amount of time, which will probably require higher traffic or user cost. The trend continues for 100, 200 and 500 nodes, until the last network size, 1,000 nodes, which generates so much expense that a $7 million debt must be paid in those ten years.

Figure 5.14. Economic impact of network size variations on user cost per minute.



Nodes	20	50	100	200	500	1000
1	($220,000)	($544,000)	($889,000)	($1,784,000)	($3,563,000)	($6,917,000)
2	($209,000)	($515,000)	($842,000)	($1,690,000)	($3,375,000)	($6,553,000)
3	($192,000)	($476,000)	($777,000)	($1,559,000)	($3,115,000)	($6,047,000)
4	($172,000)	($426,000)	($697,000)	($1,398,000)	($2,793,000)	($5,422,000)
5	($149,000)	($369,000)	($603,000)	($1,210,000)	($2,418,000)	($4,694,000)
6	($123,000)	($305,000)	($499,000)	($1,001,000)	($1,999,000)	($3,881,000)
7	($95,000)	($235,000)	($385,000)	($772,000)	($1,542,000)	($2,994,000)
8	($65,000)	($161,000)	($263,000)	($527,000)	($1,054,000)	($2,046,000)
9	($33,000)	($82,000)	($134,000)	($269,000)	($538,000)	($1,045,000)
10	$0	$0	$0	$0	$0	$0
User fee	$0.3373	$0.3068	$0.3143	$0.3273	$0.3053	$0.2983

As can be seen in Figure 5.14, the initial debt that the networking company assumes is crucial for the well being of the company. If a large debt is contracted to operate a large number of nodes, and the traffic analysis shows that traffic may not help much with the investment recovery, the project will surely die before ever being implemented.

5.2.3 Effects of Cumulative User Cost per Minute Variations

Another important variable, directly related to average traffic intensity, is the cumulative usage time over a yearly period, or cumulative operational time. This parameter may show variations not shown in the expected traffic figures, such as an increase in traffic due to a local event (fairs, celebrations or emergencies), or a decrease due to absences (vacations, long trips) at the rural community. Since traffic intensity may drastically change at any short period of time but overall cumulative time may not, these cumulative variations may have an effect on telephone service pricing figures.

So far, it has been assumed that each earth station maintains average traffic intensity at all times, but real user behavior may not be as simple to predict. A yearly operational time is a good parameter to study when designing and analyzing telephone networks. One of the advantages of modeling telephone networks is that it allows observation of this behavior and determines if there is any important impact on the estimated user cost for each model. This effect was studied and the results are presented in Figure 5.15, where the different technologies are shown regarding their cumulative operational time in minutes per year, against the estimated user cost. This study allows the designer to find the break-even point for the network economic sources, while providing insight into the technology’s performance regarding user costs.

Figure 5.15 shows that fixed assignment multiple access techniques (SCPC, MCPC) are again the technologies that provide the lowest user costs, especially MCPC with two simultaneous users. That is probably due to the low dependency on the hub for assigning channels since they already have a permanent one, so a lower user fee may be offered. In MCPC for two simultaneous users, the cost is helped by the higher revenue.

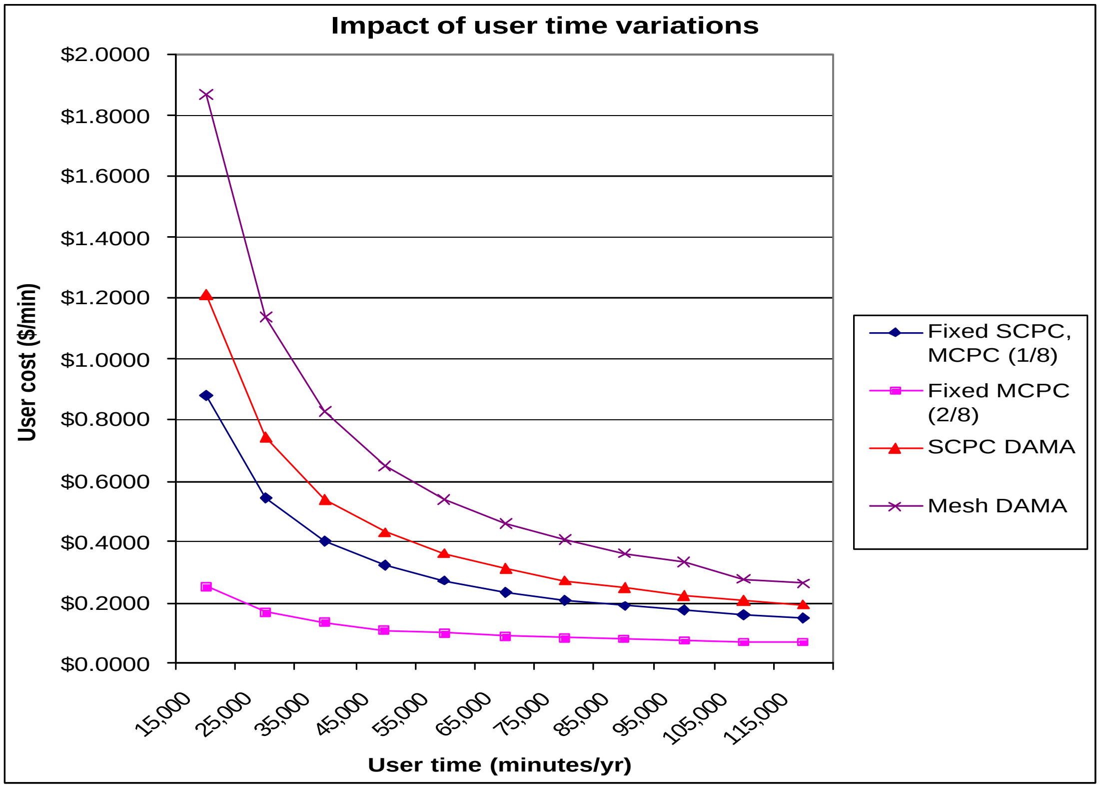


Figure 5.15 Economic impact of traffic variations on user cost per minute

SCPC DAMA also provides low costs but it needs a higher number of minutes per year than the previously mentioned two technologies. A possible reason here is that any SCPC DAMA network requires a large investment in the remote nodes (VSAT terminals) as well as a more complex hub. The maintenance cost of all VSATs is constant, although there is a reduction in the operational costs (satellite bandwidth and PSTN access). Still, SCPC provides the user with a cost-effective solution at a price within the accepted range for this work, which is under $0.50/min for medium and high traffic. This means that SCPC DAMA provides reasonable user costs for operational times over 45,000 minutes/year (about 0.085 Erlang), regarding the number of cumulative operational minutes per year for each earth station.

Finally, the Mesh SCPC DAMA model shows the least user cost-effective behavior, probably due to the high cost of the mini-hubs involved in the design, which greatly increases the overall capital and operational cost of the network. Figure 5.14 shows how only in high and very high traffic situations (more that 75,000 minutes per year, or 0.143 Erlang) can a Mesh SCPC DAMA technology deliver reasonable user costs.

5.3 Predictive Power of Models

The economic models discussed in Chapter 4 were developed with the intent to provide insight into the predictive economic behavior of different technologies applied to satellite rural telephone network design. Their implementation and results shown in Section 5.2 allow the network designer to change variable conditions in order to predict network behavior when the actual network implementation and operation takes place.

The objective when developing this type of economic model is to predict how real technologies will behave before even deciding which one will eventually be implemented. The predictive power of a model is a direct function of its ability to imitate one or more aspects of a system's or network's real-life behavior, which at some point can only be estimated if real data is not available.

Although there exist a variety of modeling and parametric analysis techniques, sometimes what is available does not necessarily solve the fundamental problem. Often, the mathematical representation of the model is not necessarily correct, or the real life system to be modeled may include parameters unknown to the system designer. The goal, then, is to be able to provide a simplified model of the system to be analyzed and to try to extract as much information from it as possible. This will not always generate the desired results, especially if the mathematical representation of the model is incomplete, or wrongly implemented in the model.

It is common in computer simulation, analysis or modeling inadvertently to introduce errors, but for that same reason, the programmer must make sure that each line of code is correct and its results are correctly displayed and interpreted. It is also common for most communications system's design to make assumptions and simplifications in order to make the problem tractable.

If the mathematical models of the system are clearly defined and understood, and correctly implemented into the analysis model, then the probability of a successful prediction of the system's behavior is high. One way to test the correct behavior of a model is by comparing the simulated model results with a real system measurement or with an analytical solution.

If the system does not have a known mathematical representation, the predictive power of the model can be obtained by means of indirect parameters, which is the case in this research. Since there are no known models for satellite telephone network design, the indirect parameter to observe in this case is the economic performance of the system, both from the investor's point of view as well as the user cost.

5.4 Summary

In this chapter, economic models for a number of satellite technologies were developed and its results presented. In Section 5.1 the analysis results for the different technologies were presented and three traffic scenarios were discussed.

In general, it can be said that for low traffic scenarios, the model projections allowed a very attractive return of investment, with the serious disadvantage that those projections were made based on a very high assumed user cost. The reason for that high value is that the network was optimized for a financial break-even point where the capital expenses were very high, which produced a large revenue when projections were made.

The main characteristic for medium traffic scenarios is that the capital and variable costs are more reasonable than for low traffic predictions. The user cost is more affordable for the typical rural user, but still allows large revenue projections over larger networks, again due to resulting user cost. Figure 5.16 shows the cost-effectiveness of the different technologies.

It was also shown that high traffic scenarios provide the lowest user cost even with reduced revenue projections ($0.20/min o $0.39/min). This behavior is due to the low user cost mentioned before. Although the user cost value would be a nice goal for the network designers, it must be clear that it was obtained using high traffic predictions, which may not materialize and revenue will not be as expected. In the second part of this chapter a comparison among the different technologies is presented, comparing different performance metrics that allow definition of the best technology for each case. The comparisons were made in terms of the effect of parameter variation upon the system's performance. These included the impact of traffic variations as an economic indicator, in this case profits, as well as varying network size on traffic and cost. Finally, a comparison of user time variations was done by comparing the total accumulated operational time against user costs per minute for all technologies studied in this research.

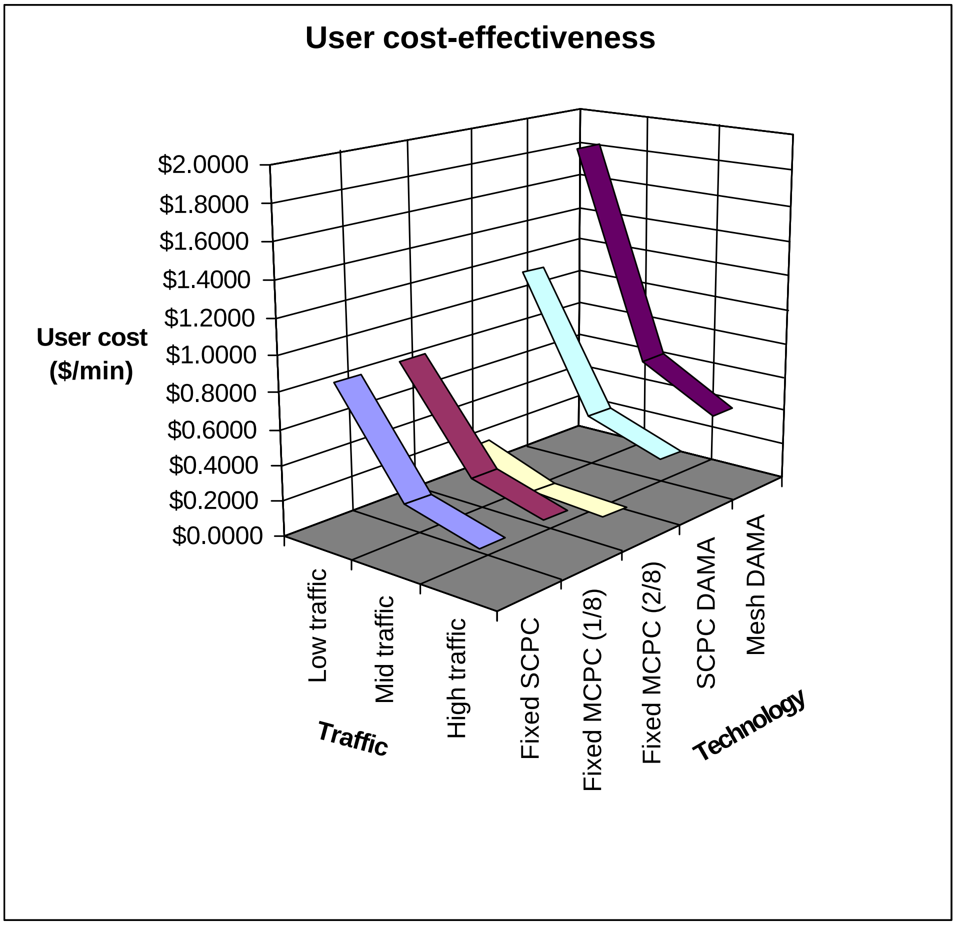


Figure 5.16. Cost-effectiveness of the different technologies.

Technology	Low traffic	Medium traffic	Low traffic
Fixed-SCPC	$0.8628	$0.3143	$0.2046
Fixed-MCPC (1/8)	$0.8716	$0.3172	$0.2063
Fixed-MCPC (2/8)	$0.2479	$0.1093	$0.0816
SCPC-DAMA	$1.1829	$0.4210	$0.2686
Mesh DAMA	$1.8282	$0.6361	$0.3976

Chapter 6

Conclusion and Recommendations

This research focused on the development and evaluation of a methodology for efficient and cost-effective rural telephone network design using satellite technology. A set of economic models to evaluate different combinations of network topologies and multiple access techniques were created and implemented, and a technical-economic assessment was performed on the different technologies under different traffic scenarios. Traffic intensity, network size and user cost per minute were optimized to achieve the network's economic break-even point under different conditions and constraints. Important parameters were identified to improve the process of effective and cost-efficient satellite rural telephone network design.

Rural telephony is a common subject of interest to most large and/or developing countries. The search for effective ways to bring telephone service to remote locations has been ongoing for decades, with technical as well as economic limitations being recurring problems. The assumption that rural telephony is not economically attractive due to low traffic or low user income has delayed telephone service implementation in most rural areas of the world. Different technologies, mainly point-to-point radio, have been proposed and used to provide this service and most of the time the service has been subsidized.

Satellite communications provides the widest coverage area of all available technologies, and mobile satellite services have been used for this purpose, but the cost of the service and that of the earth stations still limits its widespread application. It was recently mentioned at the United Nations Millennium Summit that half the world population lives with less than $2.00 a day [Ahe00]. Those people cannot afford telephone calls even with low-cost telephone service into their villages. The process of optimization for rural telephony is intended for those who can afford the service.

This research has searched for ways to efficiently and economically provide telephone service to rural communities in remote locations, with a satellite link as the access to the Public Switched Telephone Network (PSTN). Different technologies have been proposed for this purpose and a number of options have been discarded either for technical or for economic reasons, with the rural application setting at the focus.

This research effort focused on the development and evaluation of a methodology for performance optimization applied to the design of satellite rural telephone network. Common VSAT satellite network technology was used to implement the systems, and typical link budgets were designed for each case, using typical data from commercially available geostationary earth orbit satellites.

Mathematical models for the technical and economic behavior of a number of different technologies were developed using a combination of topologies and multiple access variations. These models were developed analytically and then implemented as a set of spreadsheets that allow analysis of the system performance and optimization of specified parameters. Evaluations were performed on various aspects of network design, bounded by both technical and economic constraints and applied to projections on traffic and network size to allow future network predictions and growth.

Based upon these models, important technical parameters frequently used in network design can be identified and optimized, including traffic intensity and network size, as well as economic parameters such as user cost and return on investment. This research was intended to define a methodology to model and analyze generic satellite telephone networks for rural applications, not to design specific networks or improve existing ones.

Satellite network designers and planners can use the models developed in this research to evaluate and optimize the process of network design according to their desired parameter performance requirements

6.1 Summary of Research

Chapter 1 of this dissertation provides an introduction to the problem under investigation. The rural telephony problem is presented along with the typical problems associated to this application. The economic problems and technological limitations of current rural telephone systems are emphasized, as well as the justification for using satellite communication systems for rural telephone service. The basic assumptions and simplifications used in the network design approach are discussed and presented.

Chapter 2 presents background information and literature review relevant to this effort. The fundamentals of communication systems design are presented, including other technologies that have been used for the rural telephony problem. Wireless local loops are discussed as well as their suitability for use in rural telephony. Satellite communications theory and models are discussed and different types of satellite systems are explained including those used for rural telephony and new technology. Finally, an introduction into the economic issues affecting the design of communications networks is presented, with an emphasis on technology assessment and evaluation techniques.

The quality of service in digital telephony over satellite is explained in Chapter 3. This chapter is divided between the two dominant networking technologies, the more traditional circuit-switched networks, compared against the more versatile packet-switched networks. In both cases, the discussion centers more on the quality of service parameters for real-time voice and their effect on the transmission over the satellite channel. An important part of any simulation effort is the choosing of the appropriate technology and channel models. Various satellite architectures and performance parameters are discussed in Chapter 3.

The network design methodology for rural telephone network design is presented in Chapter 4. The performance metrics required for an efficient and cost-effective network design are presented, as well as the system's technical and economic boundaries. Optimization theory is discussed and its application to communications network design is presented, with emphasis on the economic parameters that influence telephone network design. Finally, the economic models developed during this research for four different technologies are presented, along with the design sequence for optimal network design. A combination of topologies and multiple access techniques commonly used in satellite networks was applied to the rural telephone problem, resulting in the Fixed SCPC, Fixed MCPC, Star SCPC-DAMA and Mesh SCPC-DAMA economic models. The resulting sets of equations for economic performance analysis are explained and tabulated at the end of Chapter 4.

Chapter 5 contains the simulation results of the four technology models previously described, the assumptions and simplifications to make the problem tractable, and the interpretation of the results. Low, medium and high traffic scenarios provided the basis for the technical and economic assessment, based on a network of one-hundred earth stations or satellite carriers, and allowed for extended traffic and network size projections. The controlling parameters allow the behavior of different technical and economic variables to be observed, as they all change when the economic break-even point is reached at the end of the system's projected lifetime. Chapter 5 describes the performance of the network based on different optimization parameters, and compares the impact of varying factors on other network parameters, placing them in different ranks.

Appendix A contains extensive documentation of the evaluation models, including data from the different traffic scenarios and from the programs that were used to calculate the resulting worksheet.

Appendix B contains the preliminary research that produced the novel packet network architecture for rural satellite network design using a Modified ATM over Satellite (MAS) architecture and protocol. This architecture was an early result of this research, when packet switching technologies were studied to provide rural communities with digital capabilities using packet-switched networks. The architecture was limited in several aspects and the project was abandoned, although it was an early but important part of this research project.

Appendix C provides copies of conference papers that have been presented in academic events and are directly related to this research work.

6.2 Conclusions

The motivation for this research was to provide technical and economic tools that allowed an efficient telephone network design over satellite. The rural telephony problem is not new, several communications technologies have been used in an attempt to solve it, and technical and financial people agree that it is not economically attractive yet. The most commonly cited reasons are the generally low income of rural populations, which cannot support telephone service, and the expected low traffic intensity, which does not guarantee the network's viability.

The rural telephony problem was evaluated from a technical and economic point of view, using of satellite technology and produced a set of models to measure and optimize performance at a reasonable cost. This research demonstrates a method to evaluate satellite communications networks by optimizing important parameters during the design process. It has defined the most important technical and economic parameters that affect network design, and provided a novel set of economic models that result in cost-effective designs.

This research was oriented towards the development of a methodology for the optimization of technical and economic resources, and to search for the best technology for a specific problem. Therefore, part of this research involved the development of four economic analysis models for satellite network design, which allow the technical and economic performance of such networks to be predicted. Analyzing the modeling and evaluation results provides the designer with enough information to make a calculated decision regarding the economic and technical feasibility of the proposed network.

Another interesting finding was that packet-switching technology is not yet ready to provide telephone service on public networks. Packet switching technology evolved from computer networks, which have very different requirements regarding quality of service than telephone service demands. Even packet-switched satellite networks are being designed with the Internet and other computer applications in mind, with voice being a secondary application.

Broadband satellite networks are currently using generic GEO satellites with VSAT terminals, with user capacities up to 2 Mbps and feeder links up to 8 Mbps. Packet switching satellites are around the corner, and global LEO constellations will probably take a few more years to achieve financial success. Pricing algorithms are being developed for packetized voice, since the concept of length of call or distance is irrelevant in packet communications. Most systems currently charge a flat monthly fee for a quantity of data volume and an extra charge after the limit is passed.

The rural telephony problem is not yet solved, especially for the low income population, but it is a feasible solution for a large number of potential users with a higher income. Based upon the simulation results obtained from this research, it can be stated that the lower boundary of $0.25/min on user cost can be reached in certain cases, when public telephone offices are used. This is especially true when the expected traffic intensity per earth station is equal to or higher than 0.15 Erlangs (9 min/hr).

Individual rural subscribers will appear when an initial public telephone office has become widely used, people are used to making telephone calls and traffic has increased at the village level. In this case, the individual subscriber will probably have a higher income than the rest of the villagers in order to support the service. Most rural telephony systems will need to be subsidized initially before rural telephony can begin in most countries.

The solution to this problem is to help increase the rural population’s income instead of lowering user costs. Subsidies cannot last forever. With this is mind, rural telephony must be viewed as an investment for economic development, not as a public utility.

There are several specific recommendations that can be made as result of the simulations presented in this dissertation.

- The most important parameter in telephone network design is the expected traffic intensity per node or carrier. It is crucial to estimate the correct traffic value when designing a network, no easy task when previous information is non-existent. It has been shown in this research that a very small variation in traffic figures (36 seconds/hour) can create variations of $3 million in revenues or losses. The network sensitivity to traffic estimation errors makes any departure from the predicted traffic a risk factor to be seriously considered in the business plan.

- The projections for traffic and network size generated by the simulations can be misleading. The large revenues in low traffic scenarios with projected high traffic and large network can only be reached by charging a high user cost per minute, which is obtained when the low traffic simulation tries to reach the network's break-even point. When that same tariff is projected over a high traffic, large network, the resulting revenue projections are almost astronomical, up to $3.5 Billion in one case. The truth is that nobody would pay such high costs, up to $1.86/min in the same case, thus the real traffic would collapse and losses would be large. One should not lose sight of how the user cost values were obtained, especially in low traffic scenarios.

- Satellite user cost per minute is transparent to distance and applies to the satellite link only. This means the user cost is independent of the distance between the earth stations, or VSATs and Hub. However, once the call accesses the PSTN, any long distance charge between the PSTN gateway and the called site will be based upon distance, length of call and time of day. This long distance charge must be included in the call bill as an additional charge to the user, on top of the satellite link portion.

- Fixed SCPC, or plain FDMA, is recommended for small to medium size networks only, but this limitation is not based on the economic evaluation from this research. It is mainly due to the available satellite bandwidth and power, and the number of carriers that the satellite can transmit while avoiding intermodulation products between adjacent carriers. This is rather a technical constraint. Fixed SCPC is an interesting option, since it is usually regarded as a technology that wastes satellite resources. Because of its pre-assigned access nature, a Fixed SCPC network does not require complex hub nor remote earth stations, thus the capital cost per unit is smaller than with more complex technologies. The hub can be a very simple earth station with enough transmit power capacity to uplink the necessary number of satellite carriers to provide service to the network, but nothing else. The main problem of Fixed SCPC networks is the large capital investment required in the remote earth stations compared to other technologies, ranging from 35% to 40% of the total first-year investment. A Fixed SCPC network generates revenue with traffic in the low to medium traffic range (0.10 to 0.20 Erlangs, or 6 to 12 min/hr) with user cost ranging from $0.20/min to $0.42/min. This is actually a very cost-effective figure for the user, besides having an available telephone channel always.

- Fixed MCPC is recommended on medium to high traffic networks since its behavior is very similar to that of Fixed SCPC networks, only with a higher cost for the VSAT and hub earth stations. Fixed MCPC is an attractive but somehow deceptive technology, allowing the use of an earth station by multiple users over the same carrier. The most common number of TDM telephone sets in commercial systems is eight, thus promising a large amount of revenue by means of the multiple users and reduced satellite costs. In fact, revenue will be generated depending upon the expected traffic per telephone set. If there are eight telephone sets but only one is being used, that same user will have to pay for the total amount of time the connection is using a satellite carrier. For low traffic (0.05 Erlang) the probability that at least one user is calling is 28%, but for two users it drops to 5%, which means that for only 5% of the time there will be more than one person paying for the satellite carrier. This technology is definitively attractive on networks with very high traffic per node, as in medium to large size villages (500 to 1000 inhabitants) with a high traffic demand, which helps the users to divide costs. Simulation results show that a single-user MCPC network generates results in the same range as Fixed SCPC. That means medium to low traffic (0.10 to 0.20 Erlangs, or 6 to 12 min/hr) generates user costs ranging from $0.20/min to $0.42/min. When two users are calling from the same earth station, the user cost drops to less than $0.25/min for traffic over 0.10 Erlang (6 min/hr). This is the best user cost obtained in the simulations, but as mentioned, it happens only 5% of the time so it is safer to assume the single-caller user cost figures. Some existing satellite companies have decided to use MCPC networks (Intelsat, Iridium), only to find that the real traffic is less than expected and have had to change their strategy (Intelsat) or go out of business (Iridium). Again, caution is recommended when observing the projections for MCPC DAMA technology over large networks and high traffic.

- Star SCPC DAMA technology can be used when the expected traffic per node is assumed to be medium. In this research, this is between 0.10 and 0.20 Erlangs (6 to 12 min/hr), with user cost ranging between $0.32/min and $0.50/min. A Star SCPC DAMA network is recommended in situations when there is a medium to large size network with medium to low traffic, so the number of carriers allows for a good grade of service for all the network nodes. Although it is considered a somewhat expensive technology, most of the cost is generated by the multiple remote earth stations' capital cost, about 60% of the first year expenses. The relative cost of the hub is rather low, around 8% of the first year expenses, mainly due to the network management software for demand assignment, and higher transmit power capability.

- Mesh SCPC DAMA technology can only be justified when the expected traffic per node is high, or when there is a need for users to call each other and not necessarily access the PSTN. Otherwise, it is a very expensive option, with user costs ranging between $0.42/min and $0.65/min for traffic between 0.15 and 0.25 Erlangs (9 to 15 min/hr). Lower traffic intensity per node makes it even more expensive. The increase in network size helps lower user cost per minute values, but if an increase in the number of gateways is necessary, then the new gateway capital costs nullify the user cost gain. As a recommendation, in Mesh SCPC DAMA networks it is preferable to increase the traffic capacity of a mini-hub, rather than increasing the number of mini-hubs with less capacity. The increment in cost for a mini-hub with more capacity does not equal the cost of a new mini-hub, even if it means a higher long-distance telephone bill for the user.

In summary, the main thesis of this research work, that an efficient methodology can help to optimize performance and evaluate economic and technical parameters for rural telephone network design with current satellite technology, has been proved. The general panoramic of rural telephony has been discussed, since technology alone cannot solve this problem. The models developed here show that important information can be extracted from these models when correctly interpreted, and provide a general view of how a system would perform under certain assumptions.

This research has expanded the understanding of satellite network design and performance optimization. The results of this dissertation are being prepared for submission to two journals and a conference. To date, publication of three conference papers has resulted.

6.3 Recommendations for Future Research

This research effort has extended the knowledge base of satellite network design in a rural telephone environment. A novel set of economic models was developed that significantly help network designers to include performance optimization functions when designing satellite networks. While the current methodology and models provide enough insight into the network design optimization problem, extensions of this work may provide even more benefit. It is recommended that the following areas be investigated.

1. Investigate the causes that make rural telephone network design an economic as well as a technical challenge, and search for ways to further reduce user cost for technologies different to the models presented here.

2. Traffic estimation for rural telephony must be seriously researched. Traffic tendencies over time need to be established, too, since traffic is not uniform from the network's beginning to system retirement.

3. Analyze the performance of the IP and ATM packet-switching protocols regarding quality of service for real-time voice applications with large delay-bandwidth product channels, such as those found in GEO satellite networks.

4. Investigate the switching capabilities, hybrid topologies, technology-specific economic models, and pricing algorithms of broadband GEO and LEO onboard processing satellites

5. Analyze the use of operations research theory to extend the network's optimization algorithms and include the use of several constraint variables.

6. Investigate the effects of voice compression on the capacity of satellite telephone networks using different multiple access technologies.

7. Analyze the capacity improvement and protocol interaction of satellite telephone networks when interconnected to wireless local loops for local telephone/data service for cordless, cellular, PCS or third generation technologies.

8. Investigate satellite and earth station technologies for the Ka and V frequency bands using digital networks and onboard processing satellites.

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Appendix A

Network Design and Simulation Documentation

This appendix presents the documentation for the parametric design and analysis of the models used in this research, specifically the results of the low, medium and high traffic scenarios for each model.

Appendix B

Modified ATM over Satellite (MAS) Architecture and Protocol

Section 3.3 of the main part of this research mentions some of the basics of packet switching technology and briefly introduces to Asynchronous Transfer Mode (ATM) technology when used to transmit voice telephone over satellites.

One of the earlier directions of this research was oriented towards the use of ATM technology over satellites, which could allow future use on packet switched networks, especially for Internet applications. This work was not continued as the main research subject, but the basic idea is still attractive and valid, and a short description of that work is presented in this appendix.

Since the direction of this research is based on a modified version of the ATM standard, a brief description of ATM follows. This description is presented in order to introduce the parameters and its posterior variants that make the Modified ATM over Satellite (MAS) architecture and protocol models.

B.1 Asynchronous Transfer Mode (ATM) Reference Model

ATM provides an optimum protocol format for voice, video and data communications, where cells of each can be intermixed. ATM cells can be transported over SONET, SDH, E1/T1 and other popular digital formats. Cells can also be transported contiguously without and underlying digital network format.

Voice and data have very different requirements regarding time sensitivity. Voice cannot wait for the long processing and ARQ delays that are not relevant in other data applications, so ATM is able to distinguish between Constant Bit Rate (CBR) and Variable Bit Rate (VBR) applications. Voice service is typical of CBR, so for this research, all cases involved CBR over ATM Application Layer type 1 (AAL1), described next with the Broadband ISDN reference model. ATM was designed to operate over a Broadband ISDN (B-ISDN) network.

B.1.1 B-ISDN Protocol Reference Model (PRM)

ATM provides for different applications to interwork together by using a layered protocol reference model, defined by ITU-T Recommendation I.321 and called the B-ISDN Protocol Reference Model (PRM), shown in Figure B.1. It offers a mechanism based on a number of application layers with common interfaces between them and different protocols that allows immediate layers to operate together.

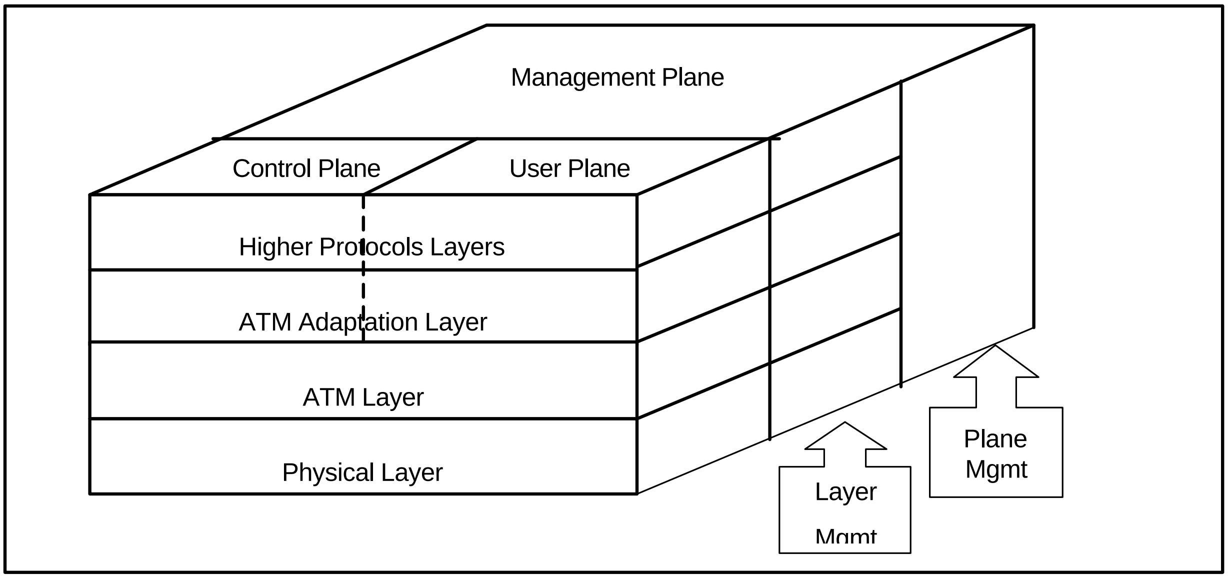

Figure B.1. B-ISDN protocol reference model (ITU-T Rec. I.321)

B.1.1.1 Cells and Packets

The terms "cell" and "packet" are often used equivalently, generating confusion as to which is which. A cell is defined as "the basic Payload Data Unit (PDU) when using packet switching. In ATM a cell consists of 53 bytes (424 bits), divided into a 5 Byte ATM header and a 48 Byte payload", as described in [Dav99]. On the other hand, the same reference defines packet as "a logical grouping of information that contains a header and/or trailer, and a payload", which in ATM would be a 53 Byte data unit, thus, a cell according to their previous definition. Wishing to avoid such confusion, in this document the following convention is established:

A *cell* is the basic payload data unit, segmented from the original information bit stream, and it is created at the Network layer of the OSI model, or its equivalent on the ATM and Internet/IP layered models, according to its specific application type.

A *packet* is the basic payload information unit created at the Data link and Network Layers of the OSI model to be transferred over the Physical Layer. An IP packet may have variable length. The ATM layer consists of a 48 Byte cell and a 5 Byte ATM header, totaling 53 Bytes. It is created at the ATM layer, according to its virtual path and virtual channel requirements.

B.1.1.2 The ATM Adaptation Layer (AAL)

The ATM Adaptation Layer (AAL) implements part of the Network and Data Link Layers at the OSI reference model, since some of its functions are to adapt and check the data for any errors. The AAL is an end-to-end Data Link protocol, allowing the ATM layer to check for errors only at the 5 Bytes ATM header. AAL checks for payload errors at both ends of the link, thus allowing a faster data transmission as shown in Table 3.3.

Service Class	Class A	Class B	Class C	Class D
Timing relation between source and destination	Required		Not Required	
Bit Rate	Constant	Variable		
Connection Mode	Connection Oriented			Connectionless
AAL protocol	Type 1	Type 2	Types 3/4, 5	Type 3/4

Table B.1 Service classification for ATM Application Layer (AAL) types

Due to the different service classes that different applications demand, multiple AAL types were defined, each with different functions and procedures that can be extracted from Table B.1.

B.1.1.3 Segmentation and Reassembly (SAR) Sublayers

The Segmentation and Reassembly (SAR) sublayer is responsible for packaging variable length data from the bit stream into fixed length 48 Byte cells for transmission, and also of unpacking the cells to reassemble the data into the final bit stream at the reception end. The Convergence Sublayer (CS) performs error checking, extraction of timing information, and helps with the reassembly of long PDUs before segmentation and after reassembly.

There are four main types of AAL, as mentioned next.

AAL Type 1. This supports Constant Bit Rate (CBR) traffic from a continuous bit stream source, segmenting it into PDUs of 47 Bytes. The AAL1 is regarded as the option when transmitting Time Division Multiplex (TDM) real-time voice (telephony) and video applications.

AAL Type 2. This provides Variable Bit Rate (VBR) traffic, needed in bandwidth efficient transmission of short packets (less than 48 Bytes). This AAL is mainly intended for low bit rate, delay-sensitive analog applications such as audio and video, which require timing information but do not have a constant bit rate. One such example would be compressed digital video or voice from a vocoder.

AAL Type 3/4. Initially AAL 3 was defined to provide VBR service on connection oriented data applications, and AAL 4 was defined to provide the same service in connectionless data services but have since merged into a single AAL type.

AAL Type 5. This protocol was developed in order to offer connection-oriented services for data applications with a lower overhead than AAL 3/4 presented. It is a simpler and more efficient AAL protocol, especially designed to match the needs of LAN equipment manufacturers and high data rate, connection oriented users [Mid99].

B.1.1.4 The ATM Layer

The ATM layer defines the structure of the ATM packet through the introduction of the 5 Byte ATM header into the 48 Byte payload cell. It is in charge of switching and routing ATM packets throughout the ATM network, with some functions of the OSI Data Link Layer. The ATM Layer defines the routing of the packet throughout the communications process by allowing other switches to read its ATM header and send packets according to its previously defined virtual route.

B.1.1.5 The ATM Header

The 5 Byte (40 bits) long ATM header contains the information required for the packet to travel the ATM network through its correct virtual connection path, previously defined when the initial connection was established. This is done by assigning a Virtual Path Identifier (VPI) and a Virtual Channel Identifier (VCI) to each packet, so the ATM switches throughout the network know how the routing will be done in each case. There are two types of ATM packets, depending upon the physical facilities faced by the packet: the end user and network interface (UNI) or between network switches (NNI).

B.1.1.6 The ATM Physical Layer

The ATM Physical Layer practically corresponds to the Physical Layer in the OSI reference model. It is concerned with the transmission of data packets over a physical communications medium connecting two ATM devices and includes all electrical, mechanical, functional and procedural functions and characteristics for access to the physical link. It is comprised of two sublayers. The first is the Transmission Convergence (TC) sublayer, which transforms the flow of cells into a steady flow of bits and bytes for transmission over the physical medium. The second is the Physical Medium Dependent (PMD) sublayer, which defines the parameters at the lowest level, such as speed of the bits on the media. This is described in [Dav99] and [ATM99], as adapting the electrical bits to the needed medium waveform, either electrical (cables, wires), optical (fibers) or electromagnetic (radio, satellite). It is in this sublayer that ATM over Satellite networking takes place, considering LEO or GEO broadband ATM networks, usually with on-board processing satellites.

B.1.1.7 ATM Routing

As mentioned before, ATM is a "connection-oriented" transfer mode, which means that although the circuit is packet-switched, the bits always follow the same path during the connection period. The process of routing in an ATM network is done by a cross-connect device called a "switch", which supports connections at the Virtual Path (VP) level, forwarding packets to other switches across the network according to a connection plan stored in memory, also called a "routing table". At the beginning of the call a virtual path is defined, so all packets follow the same route through the same ports.

Proposed broadband satellite networks are developing on-board processing technology that allows the use of the satellite as a network router, or as they call it, a "Switch in the Sky", which will allow faster routing and forwarding. Since satellites can reach longer distances, it is expected that less processing time will be required with the possibility of lower latency, although propagation time on satellite networks will still play a significant role in overall latency [Far00].

B.2 Research Plan

As mentioned throughout this work, there is a great need to provide telephone service to under-served rural communities around the world. A research goal was established, based upon the study for cost-efficient and technically sound solutions, considering the use of GEO satellite systems and broadband networks. This research proposal presented the preliminary review and technological foundations for a larger and original study on the subject or satellite rural telephony.

B.2.1 Preliminary Review of the Modified ATM over Satellite (MAS) Protocol and Architecture

This research study proposed the foundations and steps required to orient results in a rural telephony application over satellite using packet-switching technology. The defined steps to properly define the MAS model are described as follows.

- To develop a complete and integrated model of a Modified-ATM-over-Satellite (MAS) network architecture and protocols, including ATM Application Layer (AAL) protocols for classes 1 and 2. Protocols for AAL classes 3/4 and 5 may also be implemented, if deemed necessary.
- To test all user and management protocols in a Matlab simulated environment, under bit and burst error conditions similar to those found in digital satellite transmissions.
- To implement the MAS architecture and protocol models into the OpNET modeling tool for GEO satellite rural telephony and digital networks.
- To simulate a hypothetical rural telephone network under varying traffic loads, network size and propagation conditions, and observe the Quality of Service (QoS) indicators and other important parameter's performance.

B.2.2 Expected Results

This research work has allowed the study and analysis of satellite rural telephone networks, its main characteristics, parameters and quality indicators. It can also allow the integration of a computer network standard such as ATM to a voice network like rural telephony. It allows the study of communications theory from a systems level to the solution of a specific problem. The expected results from this work were:

- The study of packetized voice transmission via a GEO satellite, and its latency and information degradation effects in its desired Quality of service.

- The application of the systems engineering process to basic telecommunication systems design considering the life cycle process approach.
- The development of a simulation tool for ATM-compatible packet transmission and reception for voice and data.
- The definition and specification of a new set of user and management protocols for an ATM-compatible network
- The development of a new OpNET module for user and management traffic in an ATM-compatible VSAT network simulation through a GEO satellite.

B.2.3 Expected Contributions

Once this study were completed, a comprehensive and integrated analysis of the MAS network architecture and protocols would be obtained. The following aspects were considered original and to be new contributions in this analysis.

- Previous technologies have tried to solve the satellite rural telephone problem by means of low bit rate voice transmission through circuit switched networking satellites, mainly on a narrowband RF channel using Demand Assignment Multiple Access (DAMA), with no possibility for higher bit rate applications. In this work it could be possible to use packet switching technology that allows the transmission of other applications as well as voice. Bit rate capacity could be increased, although it would still depend upon the Remote Earth Station (RES) transmit power limitations.
- Practically all ATM satellite systems currently operational or proposed include the full ATM header during the satellite link, thus increasing bandwidth and bit rate, or decreasing throughput. Satellites without on-board processing capacity do not use this field, which further reduces system throughput and adding processing delay to overall latency. Satellites with on-board capacity are out of this research boundaries due to increased costs and complexity.
- The MAS network architecture was planned to optimize overall latency and Quality of Service in real-time applications such as voice transmission through GEO satellites.

- A new network architecture would be developed and specified, including the definition of its protocol layer stacks for different applications, packet and parameter fields, as well as its corresponding interfaces.
- The new architecture was expected to provide rural users not only with telephone service, but also with new digital packet technology, fully compatible with one of the newest information network technologies, ATM. Multiplexing capacity was included at each terminal.

The use of widely available VSAT technology, although not new in satellite rural telephony, is being used for ATM-compatible transmission over generic GEO satellites. Most future ATM-capable satellite systems will feature on-board switching and processing, requiring special portable terminals or telephones. The MAS architecture allows for common wired or wireless connection to the Remote Earth Station.

B.3 Preliminary Research Results

This study describes the design of satellite rural telephony networks as a primary function, with the capability to offer transmission of other packet-switched data applications over the same network as a secondary function. The main goal in rural telephony network design is to provide a cost-efficient telephone service to rural communities by offering Quality of Service through the use of the best possible technology available.

After a long time studying currently available technology for satellite rural telephony, it was found that several networks, architectures and technologies are currently offered by different companies throughout the world. Nevertheless, none of them gives enough attention to the boundaries previously set on Section 3.3 on this same document for a satellite rural telephone system, therefore a new or modified architecture and protocols were needed.

ATM was chosen as the main standard to work with due to its many advantages regarding voice transmission as well as multimedia capabilities and almost universal compatibility with most Public Switched Telephone Networks (PSTN) around the world. A few modifications were made to the standard ATM architecture and protocols, which give a better performance over the satellite segment for the desired application.

B.3.1 Initial System Architecture Definition

A telephone network needs to be designed for a rural community at both the local area for local traffic as well as the long distance link to the PSTN or other digital communication networks. In the case of rural communities with varying population sizes, the local area problem is to be avoided, rather focusing this work on the long distance connection via satellite.

One important objective is this work is to be used in future digital communications networks for both voice and data applications, as well as low-bit rate video services, such as Tele-conferencing and Tele-education. With that objective in mind, and due to the growing presence of networks carrying all types of digital multimedia, this work will try to fit the specific application of voice, in this case telephony, through a packet-switched architecture for public communications networks. This work is based on the increasingly popular Asynchronous Transfer Mode (ATM) technology, a packet-oriented transfer mode to be used over a Broadband Integrated Services Digital Network (B-ISDN), which allows the delivery of high bit rate services and integrates video, voice and data through a single network infrastructure [Dav99].

Since ATM was designed to operate over B-ISDN channels, which are mostly based on fiber optic lines, the introduction of ATM over satellite channels has brought many new challenges, which have been studied extensively [IEEE97, IEEE99-1, IEEE99-2]. Nevertheless, the problems and proposed solutions involved mainly data (Internet) and high-speed video transmission, and invariably from urban sites. Thus the specific area of telephone transmission from rural sites has not been studied with enough intensity so as to provide a cost-effective, technically sound network design. This work is headed in that direction, proposing a modified version of the ATM standard, specially adapted for telephone networking through a generic Geostationary Earth Orbit (GEO) satellite. The objectives are to provide a telephone Quality of Service comparable to land telephone lines, only with higher latency due to the satellite link.

B.3.2 Quality of Service Indicators

A network architecture and protocol will be defined based upon QoS parameters that provide efficient network design and service. The traffic parameters to be closely followed will be Peak Cell Rate (PCR), Sustainable Cell Rate (SCR), Minimum Cell Rate (MCR) and Maximum Burst Size (MBS), which will define the QoS of the desired services (CBR over AAL 1 and VBR over AAL 2). To obtain this, it is needed to negotiate a traffic contract that provides

QoS on network parameters such as Cell Loss Ratio (CLR), Cell Delay Variation (CDV) and Cell Transfer Delay (CTD). All parameters mentioned above will coexist in an environment composed of a Modified ATM over Satellite (MAS) architecture and protocol, explained next.

B.3.2.1 Latency

The MAS architecture was designed based upon minimizing end-to-end delay during the satellite segment of the network. Although propagation time can not be reduced, a number of small functions were eliminated with the ATM and Physical Layers, not considered during the satellite portion of the network operation.

B.3.2.2 Bit and Packet Errors

Bit error rate (BER) and Packet error rate (PER) indicators will be monitored during the simulation process in order to provide an overview of the MAS network performance. Random errors at the bit and burst levels will be simulated following various probability density functions, according to typical performance measurements.

B.4 Modified ATM over Satellite Network Architecture and Protocols

B.4.1 Overall MAS Network Architecture

A new point-to-multipoint satellite architecture for digital networks has been developed as part of this research involving a VSAT-like packet network transmitting ATM payload cells. A low operational cost is expected by using typical transponder bandwidth on a generic bent-pipe GEO satellite using low cost VSAT remote terminals a star configuration network. Any available RF frequency band can be used on this network, depending upon available satellite coverage and bandwidth. Low capacity VSAT remote earth station terminals are used for rural access applications.

The private digital network consists on up to 256 Remote Earth Stations (RES) and one Gateway Earth Station (GES) with a back-up, interconnecting the remote private networks to a public or another (larger) private network as shown in figure 4.1. Both telephone and data networks can operate on this architecture, according to its payload type and ATM Application Layer (AAL) .

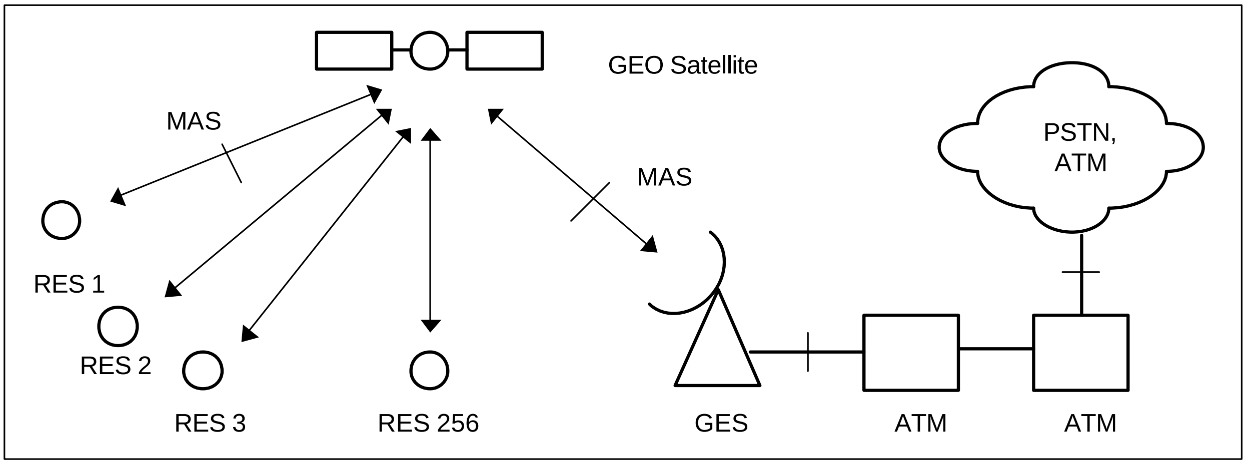

Figure B.2. Modified ATM over Satellite (MAS) network architecture

Each RES can be connected to a local digital communications network (LAN, ATM, telephone), allowing satellite access to up to 4 switched or multiplexed simultaneous users per remote site, and up to 1024 simultaneous users on the complete satellite network. This system uses an ATM-compatible architecture suitable for cell and packet transmission over a GEO satellite network.

Modifications are made in order to adapt the system to a large delay connection so that it does not require waiting for acknowledgment. A remote LAN, ATM or wired/wireless digital telephone network can be connected to the Remote Earth Station (RES) for long-distance satellite routing to a private or public data network, as well as the PSTN, through a Gateway Earth Station (GES). The GES is the heart of the satellite-based system; it controls the RES VSAT network and acts as a gateway to the digital packet-switched networks.

B.4.1.1 Remote Earth Station (RES) Architecture.

The Remote Earth Station is based on a number of subsystems that help deliver information both ways: a packet to the satellite network, and user data to the local network. This is accomplished by means of several interfaces, some of them standardized and some of them especially designed for this architecture, which is called MAS network architecture. In the case of voice (telephone) transmission, the ATM Application Layer's Segmenting And Reassembly (SAR) subsystem, which segments the received voice (or any other application, in a general case) into typical ATM payload cells and adds the corresponding AAL header.

This is creates a standard ATM cell (48 Bytes), but it is not yet an ATM packet (no ATM header has been included). Figure B.3 shows the basic RES architecture.

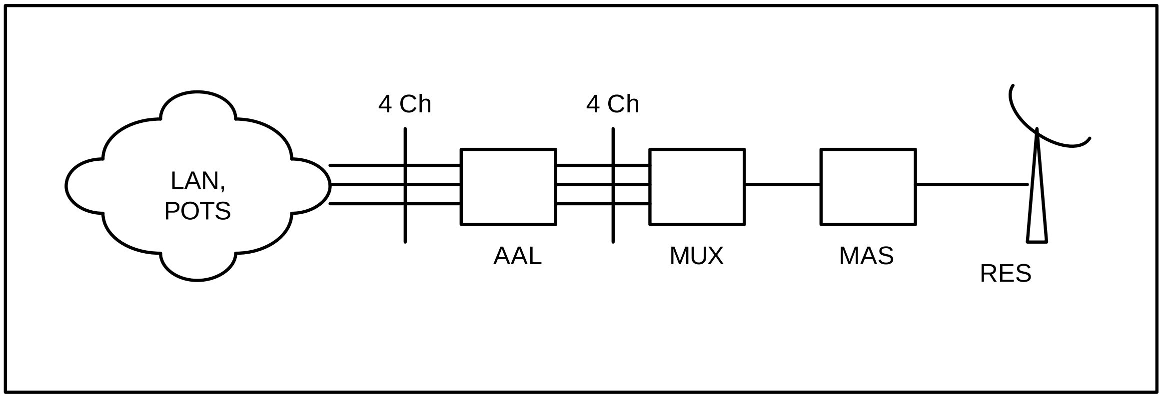

Figure B.3. Remote Earth Station architecture

The RES then adds a Modified-ATM-over-Satellite (MAS) header and trailer, thus creating a special satellite packet, which is then sent over the satellite channel. Satellite multiple access is a choice between SCPC-DAMA and Slotted ALOHA, since overall latency and propagation delay is crucial in this application. Bit rate is also limited due to bandwidth and transmit power at the VSAT terminal

B.4.1.2 Gateway Earth Station (GES) Architecture.

The receiving Gateway Earth Station is the most important element of the MAS architecture. It receives the multiplexed (or switched) channels from each RES and routes the packets to a MAS-to-ATM converter interface system. It discards the MAS header and coding, then adds a standard ATM header to each packet and sends it to the ATM-based network or to the PSTN if needed, thus reducing latency and need for retransmissions.

If the application is real time, such as voice or video, it ignores bit errors that do not affect the Quality of Service (QoS) below a predefined threshold. If the application is non-real time, such as data, the GES demands a retransmission from the RES, thus increasing system latency and hurting overall throughput. An ARQ variant is used for this situation.

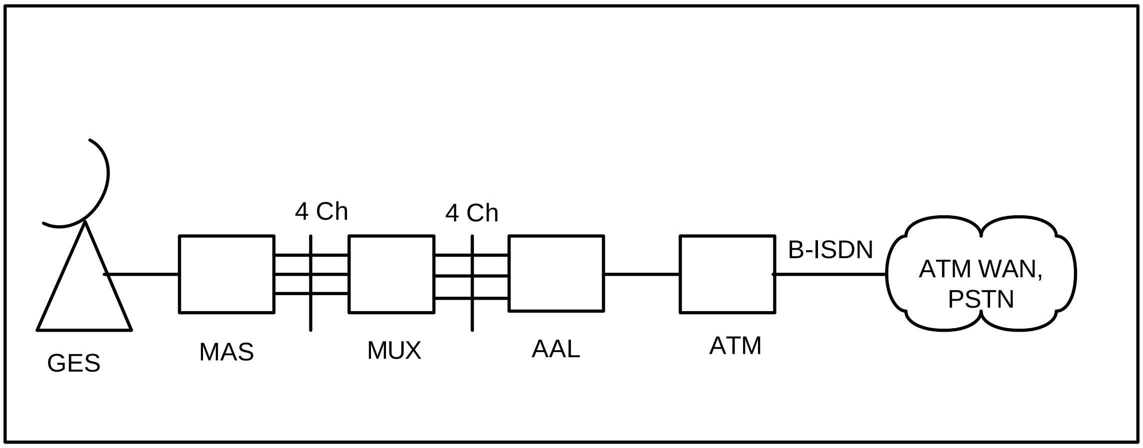

Figure B.4. Gateway Earth Station (GES) architecture

B.4.2 MAS Protocol Layer Architecture.

The MAS protocol must be properly integrated into the new network's protocol layer architecture, which helps define all new interfaces in the whole network, basically at the RES and GES ends of the satellite link. This will allow illustrating what element is needed at which stage, in order to correctly specify the new network architecture. Still, it must be able to interact with standard ATM interfaces at the output of the GES's MAS segment, therefore the upper layers of the MAS protocol must comply fully with the ATM standard protocol throughout the network, as shown in figure B.5. The MAS management protocol stack must follow this requirement, too.

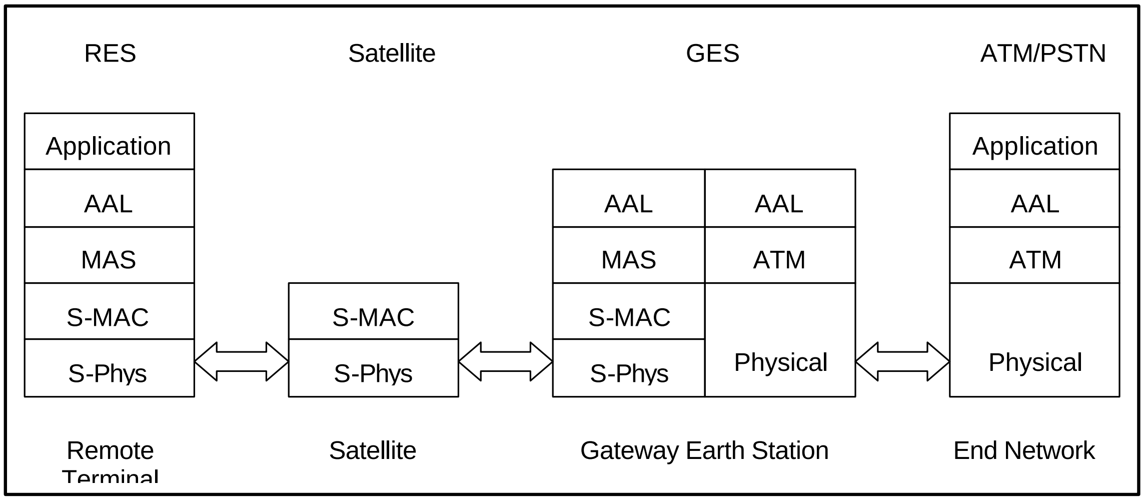

Figure B.5. MAS protocol layer architecture.

As Figure B.5 shows, the MAS network architecture does not depend on on-board processing satellites, and ATM switching is not performed during the satellite link segment, therefore no virtual paths or channels are needed. The MAS packets are addressed between RES and GES through their unique RES and MUX user fields in the MAS header. After the MAS packet is received at the GES, it correctly identifies the user station and channel, drops the MAS overhead and creates an ATM Virtual Path and Channel (VPI/VCI) field at the new ATM header on a UNI interface.

These new fields are created at the GES during the initial set up at the beginning of the call, and define VPI and VCI information. The GES' main function is to correctly route packets between the ATM and the MAS networks, thus requiring much computational power (memory, buffering, high-speed routing, packet re-assembly) for network operation as well as network management functions. The high complexity demanded from the Gateway Earth Station is balanced by the simplicity (and lower cost) of the satellite and multiple Remote Earth Stations.

B.4.2.1 MAS network traffic capacity.

The proposed MAS network architecture allows up to 256 remote earth station to communicate to a larger network via satellite through the GES. An important parameter in any communications network is its traffic capacity at certain load traffic. Since each RES RF carrier allows up to 4 AAL 1 multiplexed users, theoretically it could serve 1024 Continuous Bit Rate (CBR) simultaneous users, but telephone theory shows that, depending upon the expected or measured traffic, many available telephone lines will be idle most of the time. It is important to define the required satellite RF bandwidth for the MAS network, since this will heavily affect the viability of the rural network.

Defining the correct multiple access technique to the satellite is crucial in this phase of the network design, since it allows the network's RF channel specification with considerable less bandwidth than the required in a fixed Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) environment.

In the first case the FDMA network requires one RF channel for each RES, resulting a very large satellite bandwidth, which is expensive for the network operator, and if unused most of the time results in an inefficient network design. On the other hand TDMA requires higher data rates and, therefore, more carrier bandwidth, which demands larger antennas and powerful transmitters at the RES, thus increasing the overall cost of the network.

For a 256 RES rural network at 128 kbps per terminal at QPSK, with 0.25 Erlang traffic per RES would require 64 100 kHz channels (6.4 MHz total satellite bandwidth) if a SCPC-DAMA multiple access is used.

B.4.3 MAS Protocol Specification

B.4.3.1 MAS Protocol Packet Model

The new protocol created in this research has been designed to allow all RES stations in the network to communicate with the Gateway Earth Station as required by the MAS satellite system architecture. The new protocol includes information regarding the application type, its cell information as well as its RES of origin and multiplexed port at that specific RES. Next, the MAS protocol is explained, along with an indication of each bit field in it.

The Modified-ATM-over-Satellite (MAS) packet was assigned the bit distribution shown in the following figure. The payload data may be any type of data, segmented according to its ATM Application Layer (AAL) category (CBR, VBR, ABR, etc.) but its total packet length must always be 53 Bytes (424 bits), as shown on Figure B.6 for AAL type 1 (CBR). The same figure also shows the percentage of user information (payload), which helps explain the protocol's information carrying efficiency (almost 89%).

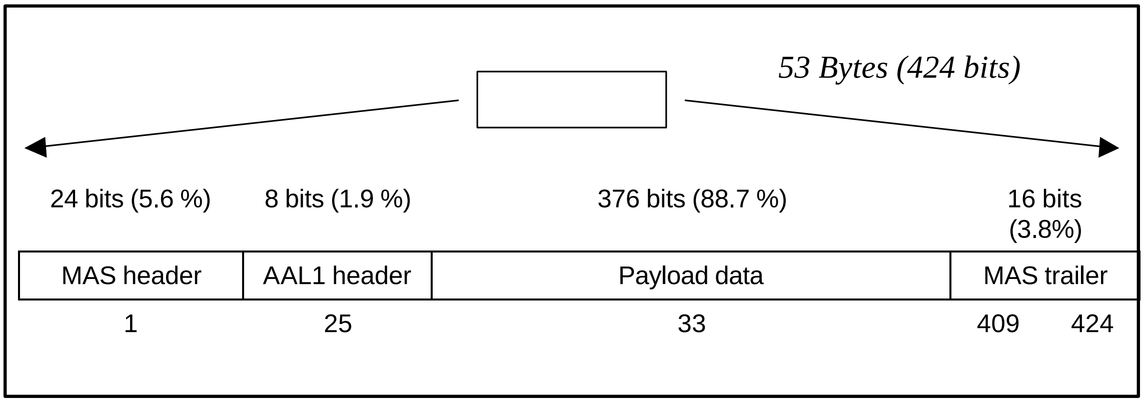

Figure B.6. General structure of the MAS packet model and overhead distribution for AAL 1.

B.4.3.2 Structure of the MAS User Protocol Model.

The MAS protocol structure is presented next for real-time voice transmission, as it would appear on the rural telephony case. The parameters presented are assuming Constant Bit Rate (CBR) service, class 1 ATM Adaptation Layer (AAL1) and the required MAS header and trailer to be used over the MAS network. Figure B.7 shows this process from application to MAS physical layers.

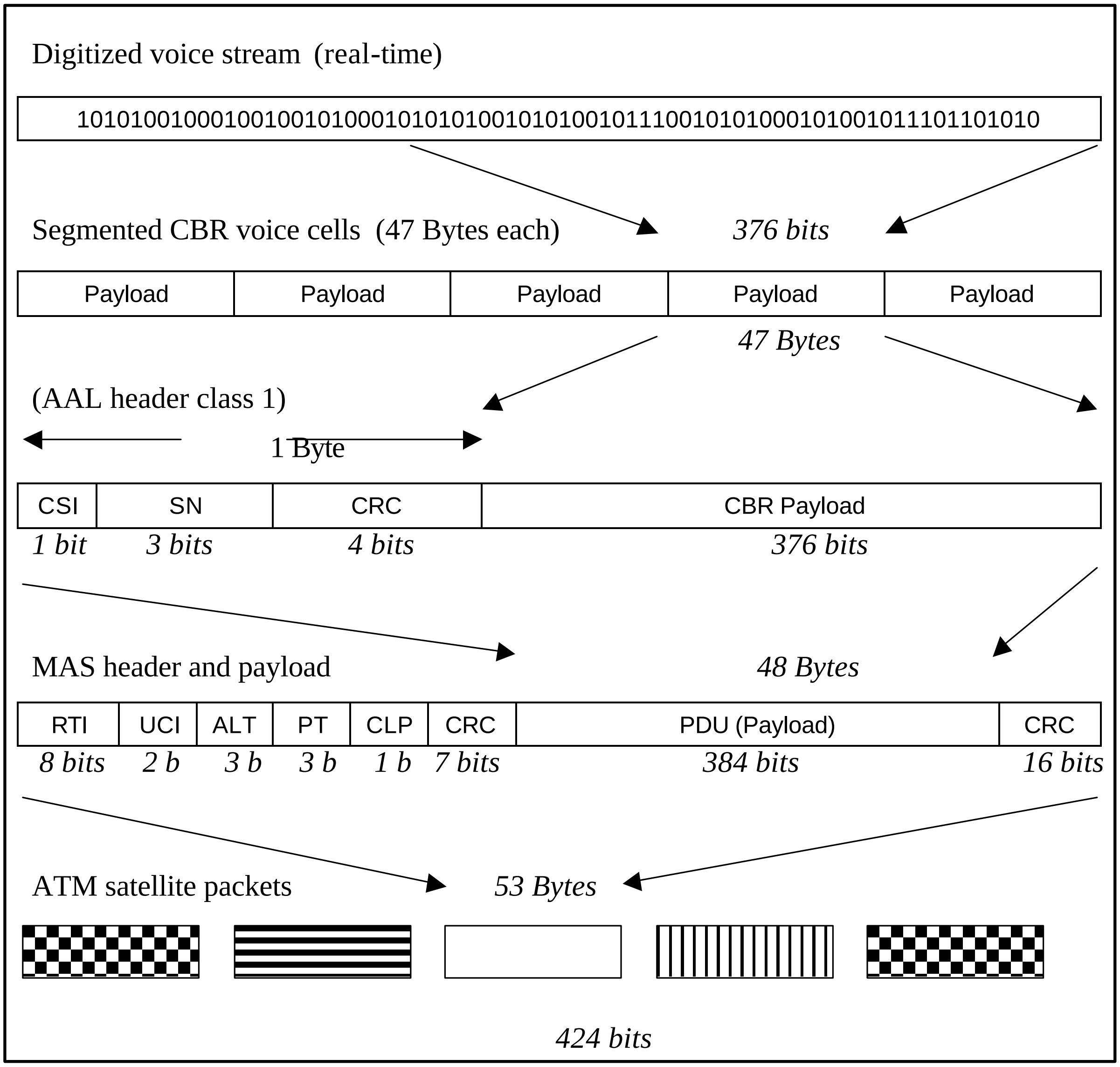

Figure B.7. Protocol reference model for MAS packet encapsulation (AAL type 1 case)

Table B.2 describes each parameter shown in Figures B.7 and B.8, and their individual position in the MAS packet along with some comments. An important issue to be described in detail later is that the MAS packet uses three different error control fields with a different application each, as explained next.

The AAL header includes a CRC field at the end of the header, which is part of the ATM standard and is used to detect and correct bit errors that may have been introduced during the packet transmission. This field uses a 4-bit error detecting and correcting code, which allows correction of any change at the AAL header Convergence Sublayer Indicator (CSI) and Segment Number (SN) fields. All headers must have ample redundancy to allow recovery of the header information and avoid losing the complete packet.

The MAS header also includes a CRC field, also called Header Error Correction (HEC) field, which is a 7-bit error detecting and correcting code that ensures the correct addressing of the MAS packet over the satellite link. It keeps the RTI, UCI, ALT, PT and CLP fields from bit errors that could affect the packet's correct addressing.

The MAS trailer includes the PED, which is a 16-bit error detecting-only field, used to detect error in the payload. If an error appears, it signals the GES about it and depending upon the packet's application it request a retransmission (data transmission case only) or allow the packet to be used as it is (real-time voice and video cases). The reasoning behind this choice is a crucial one: speed vs. precision.

It is assumed that real time applications such as voice and video include a great deal of redundancy and a few bit errors can be accepted as long as the packet is not lost. In this case a retransmission request over the satellite link will greatly affect the QoS of the real-time application. On the other hand, precision is more important for data transmission, so if payload errors are detected at the receiving end of the link a retransmission is requested and the erroneous packets are sent again.

The receiving terminal, either RES or GES, will accommodate the received packets and will wait for the retransmitted packet to arrive before delivering the subsequent packets in the initial order of presentation. This requires a Selective Repeat ARQ (Automatic Repeat Request) type of coding, and a great deal of buffering at both ends of the link. The receiving earth station will make this choice based upon the Application Later Type (ALT) field on the MAS header, which indicates the class of service being transmitted (CBR, VBR, ABR, etc.) on its 3-bit field.

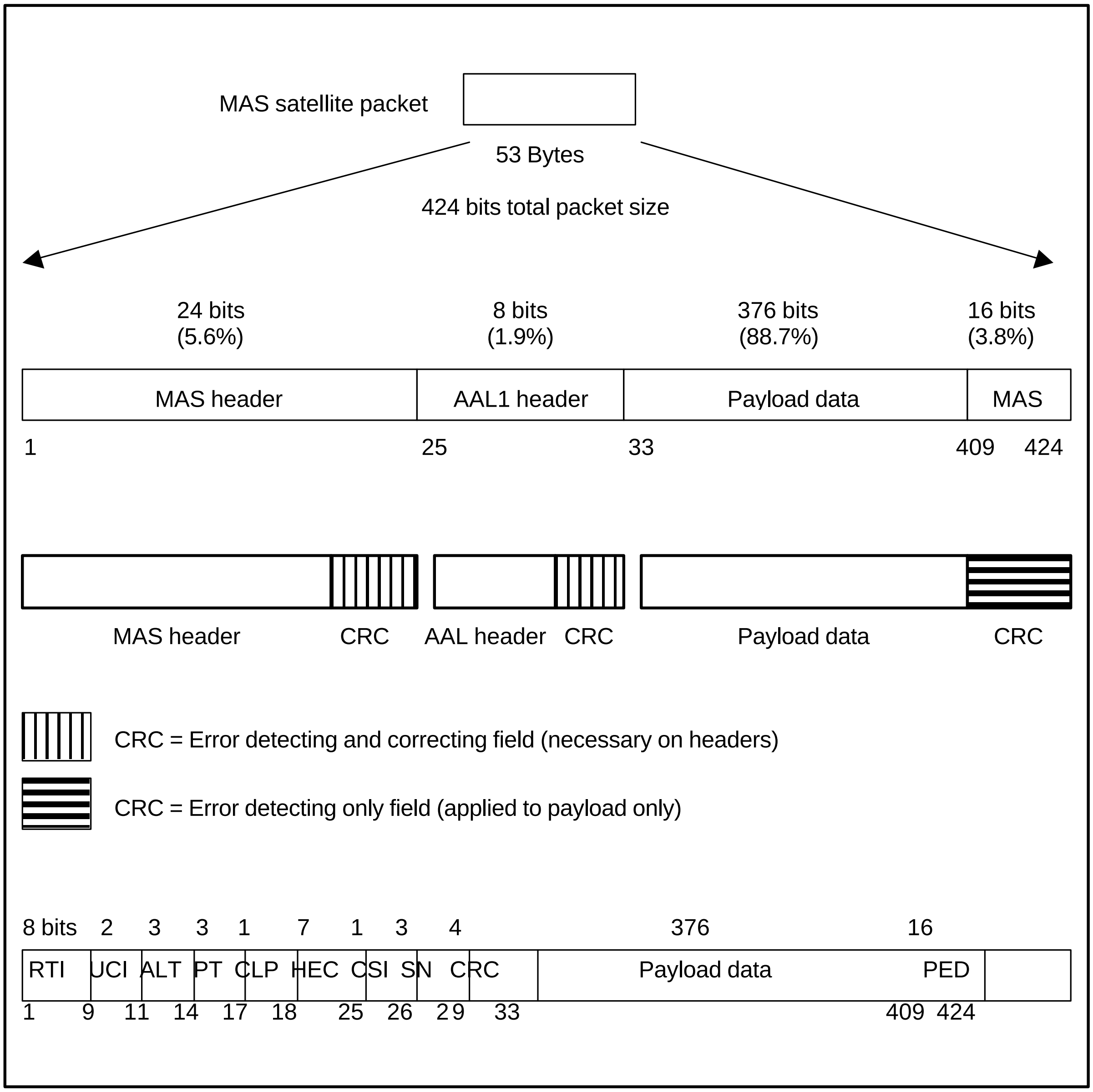

Figure B.8. Structure of the MAS packet: MAS header and trailer, AAL 1 overhead fields

Table B.2. Elements of the MAS packet protocol

	Description	bits	Comments
RTI	Remote Terminal Identifier	8	256 Remote Earth Stations possible
UCI	User Channel Identifier	2	1 to 4 TDM multiplexed users per RES
ALT	Application Layer Type	3	Up to 8 possible AAL types possible
PT	Payload Type	3	Part of ATM header, indicates management/user cell
CLP	Cell Loss Priority	1	Part of ATM header indicates high/low priority
HEC	MAS Header Error Correction	7	(24,17) MAS header error correcting code
CSI	Convergence Sublayer Indicator	1	On AAL, describes ATM/non-ATM format
SN	Segment Number	3	1-8 Sequential numbering of payload cells
CRC	Cyclic Redundancy Check	4	(8, 4) AAL1 cell header error correcting code
PDU	Payload Data Unit	376	AAL1 Payload data (CBR user cell, 47 Bytes)
PED	Payload Error Detection CRC	16	Payload error detection only, no correction
MAS	Modified ATM over Satellite	424	Total modified ATM packet for satellite network

B.4.3.3 Structure of the MAS Management Protocol Model.

Although the MAS management protocol model has not yet been implemented, it will be part of the specification. It will involve the management plane shown in Figure B.1 for both layer management and plane management. Management functions will be included into the MAS protocol and will be compatible with standard ATM management functions.

B.4.3.4 Structure of the MAS Error Control Coding Models.

The CRC field included in the AAL header part of the ATM standard and is used to detect and correct bit errors that may have been introduced during the packet transmission. This field uses a 4-bit error detecting and correcting code, which allows to correct any change at the AAL header Convergence Sublayer Indicator (CSI) and Segment Number (SN) fields. All headers must have ample redundancy to allow recovery of the header information and avoid losing the complete packet.

The CRC field included in the MAS header, also called Header Error Correction (HEC) field, is a 7-bit error detecting and correcting code that ensures the correct addressing of the MAS packet over the satellite link. It keeps the RTI, UCI, ALT, PT and CLP fields from bit errors that could affect the packet's correct addressing.

The MAS trailer includes a final field called PED, and it is a 16-bit error detecting-only field, used to detect error in the payload. If an error appears, it signals the GES about it and depending upon the packet's application it request a retransmission (data transmission case only) or allow the packet to be used as it is (real-time voice and video cases).

The reasoning behind this choice is a crucial one: speed vs. precision. Voice and video may accept a few bit errors since a retransmission delay over the satellite link will seriously affect its QoS, so no retransmission is requested. Precision is more important for data transmission, so when errors are detected a retransmission is requested, thus ensuring a high precision transmission, if a delayed one. The information required for this choice is sent at the Application Later Type (ALT) field on the MAS header.

MAS Multiple Access Algorithm.

As mentioned before, a final decision has not yet been made regarding the satellite multiple access to be implemented in the MAS network. It is a very important decision, since it will define the architecture's efficiency, and it seems highly possible that it may be some form of Demand Assignment Multiple Access (DAMA) or Slotted Aloha with Reservation. This is because both techniques allow an efficient use of the satellite system's bandwidth.

B.5 Case Simulation of the MAS Protocol Model

The initial steps for the MAS protocol model have been implemented using the Matlab environment in order to test its viability and protocol complexity. A number of MAS user packets were generated following the MAS protocol stack shown in figure 4.8. A user application consisting on Continuous Bit Rate (CBR) data at the upper layers was converted into MAS packets using the ATM Application Layer type 1 (AAL 1), and the main MAS protocol layers were implemented and compared before and after overhead was added.

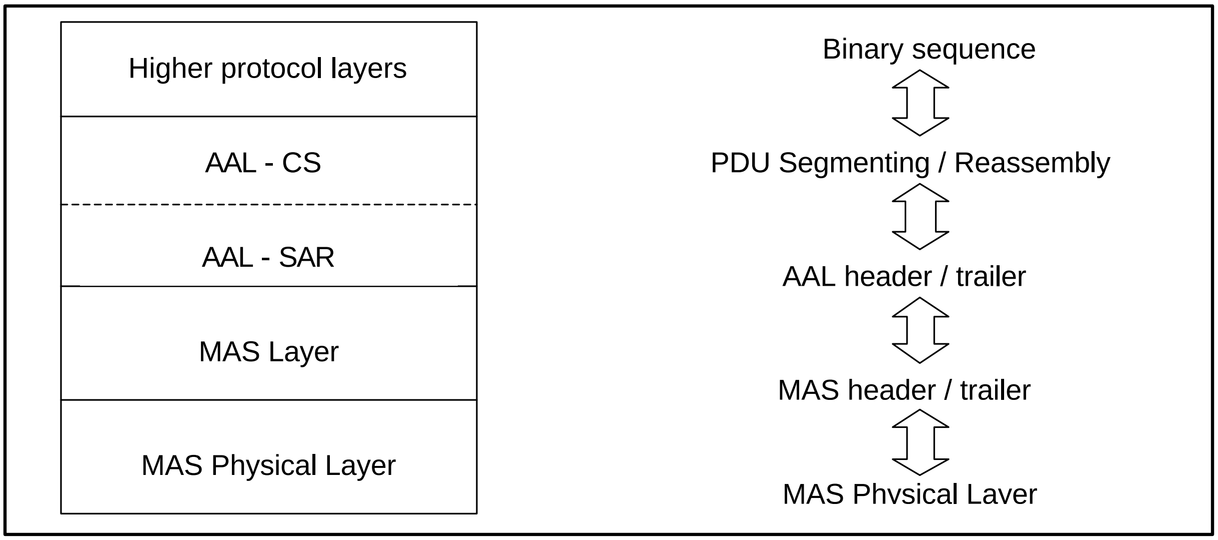

Figure B.9. B-ISDN protocol reference model and simulation implementation sequence

Figure B.9 shows the different layers and the required interfaces and functions in sequence. Since each step must be carefully implemented, several algorithms were created for each interface in this specific case (CBR on AAL 1). A number of interface algorithms will need to be implemented for each different case in order to make the MAS network be part of a complete protocol and interface specification. The simulation process is explained in Figure B.10, where the sequence of events indicates each simulation step required when generating a MAS packet.

B.5.1 MAS Model Simulation Sequence

A simulated communications system was developed in order to test the MAS protocol, including a basic transmitter, a transmission channel and a receiver. The simulated system did not include any physical layer elements, since that subject is out of the scope of this work.

Nevertheless, binary transmission was generated and different elements of the MAS protocol were implemented and tested. The simulation sequence is shown in Figure B.10 and is briefly explained next.

The first step was to generate the binary sequence representing a digitized voice bit stream with enough data to simulate at least several hundred microseconds of voice. The resulting binary sequence was tested for average distribution, presenting a probability of occurrence of 0.5 for both ones and zeroes in sequences longer than 2 kbits. Four binary sequences were generated to provide different bit streams.

The second step was to segment the bit stream into payload data units (PDU), or payload cells, according to the proper AAL convergence sequence and defined cell size. The resulting Packet Data Units (PDU) were then reassembled and compared to the original sequences.

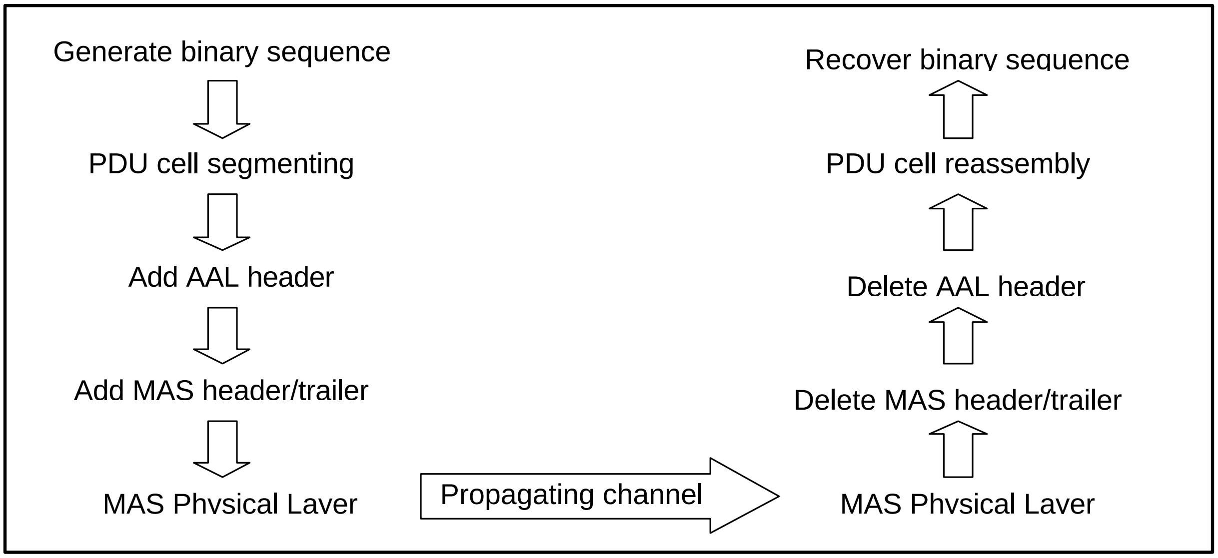

Figure B.10. MAS model simulation sequence

The third step was to add the AAL header to the PDU, in this case AAL 1 was used, and a 48 Byte ATM payload cell was generated. The resulting cells were then separated from the AAL header, reassembled into the original binary sequence and successfully compared to the original sequences.

The fourth step was to take each new payload cell and add the MAS header and trailer, creating a MAS packet in each case. Once the MAS packets were complete, a transmission channel was simulated in order to introduce errors in the information according to a previously established Bit Error Rate. At this stage the simulated channel has a characteristic value of 1 and no errors are being introduced since the error control coding elements of the MAS protocol are not yet ready.

The received MAS packets were disassembled retrieving its MAS overhead from the AAL cell, then the AAL header from the PDU segment and finally reassembled the payload successfully into the original binary sequence.

The next step would be to actually simulate the MAS physical layer, but it was decided to avoid that part since it is not into the scope of this work. The physical layer parameters, including RF signal modeling (modulation, etc) will not be implemented in this research.

Once the MAS layer packets are ready, a link simulation will follow, introducing a random number of errors into the transmitted information. The errors will be simulated as changes from ones to zeroes and vice-versa, according to a previously defined BER value. Errors will be presented as bit errors and burst errors, to properly characterize typical satellite propagation impairments. This stage has not been implemented yet, since a review of error control theory needs to be done before introducing errors into the simulation.

When that part is ready, independent uniformly distributed errors will be introduced for the bit error case, and larger blocks of errors will be used for the burst error case. Basic error detection and possible correction will be included into the MAS protocol headers and trailers in order to avoid or minimize the number of requested retransmissions.

B.5.2 MAS Simulation Model Parameters

B.5.2.1 Binary Sequence Generator

The initial stage of the MAS protocol simulation has been implemented using a Matlab environment, regarding the generation of 4 pseudo-random binary sequences. In the first case a generator with register length 14 and primitive polynomials [1, 6, 10, 14] was used, as described in [Jer92], Table B.3, generating 16,384 pseudo random bit sequence and shown in Figure B.11. The four binary sequences provide different bit streams using linear shift registers of length 14 (taps [1, 6, 10, 14]} and length 15 (taps [1, 15], [1, 5, 10, 15] and [1, 3, 12, 15]) from [Jer92].

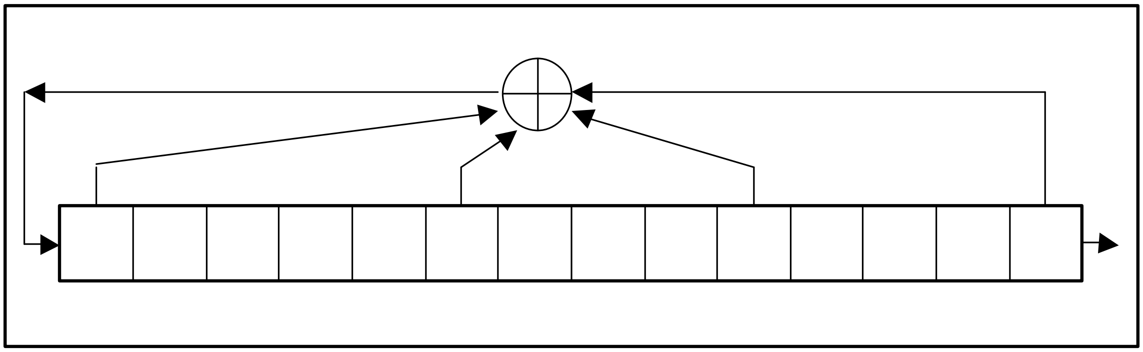

Figure B.11 Linear shift register generator of length 14 associated with taps [1, 6, 10, 14]

Once the other binary sequences were generated using four different polynomials of length 14 and 15, the MAS Segmentation and Reassembly (SAR) sublayer was implemented for CBR service on AAL 1. A similar process will follow for VBR service over an AAL 2 model and if deemed necessary, the same for AAL types 3/4 and 5.

B.5.3 Binary Sequence Segmentation Algorithm

The binary sequence is segmented into Payload Data Units (PDU) consisting of 376 bits (47 Bytes) for AAL 1. The variable *InitialPayload(j)* is the original bit stream generated by the binary sequence generator and the variable *UserData(i,j)* is the j_{th} bit of the i_{th} PDU. The segmentation algorithm used is presented as follows.

$$\mathit{UserData}\ (i,\ j) = \sum_{i=1}^{\infty}\sum_{j=1}^{376} \mathit{InitialPayload}\ (376\,(i-1)+\ j)$$

B.5.3.1 AAL Header Assembly

The AAL 1 cell is called *UserCell*, and is a 384-bit cell by adding an 8-bit AAL header comprised of 3 data fields: a 1-bit Convergence Sublayer Indicator (*CSI*), a 3-bit Segment Number (*BinSegNum*) and a 4-bit Cyclic Redundancy Check (*AAL_CRC*). This header is followed by the PDU (*UserData*), as follows.

$$\mathit{UserCell}(i,\ j) = \sum_{i=1}^{\infty}\sum_{j=1}^{384}\left(\mathit{CSI}(i,1) + \sum_{k=1}^{k=3}\mathit{BinSegNum}(i,k) + \sum_{k=1}^{k=8}\mathit{AAL\_CRC}(i,k) + \sum_{k=1}^{k=376}\mathit{UserData}(i,k) \right)$$

B.5.3.2 MAS Header and Trailer Assembly

The MAS packet is called *Packet*, and it includes the 8-bit Remote Terminal Identifier (*RTI*), a 2-bit User Channel Identifier (*UCI*), a 3-bit Application Layer Type (*ALT*), a 2-bit Payload Type (*PT*), a 1-bit Cell Loss Priority indicator (*CLP*) and a 7-bit MAS Header Error Correcting (*HEC*) code. This header is followed by the AAL payload cell *UserCell* and appends the MAS trailer at the end, called Payload Error Detection (*PED*) code.

$$Packet(i,\ j) = \sum_{i=1}^{\infty} \sum_{j=1}^{424} \left(\sum_{k=1}^{8} RTI(i,k) + \sum_{k=1}^{2} UCI(i,k) + \sum_{k=1}^{3} ALT(i,k) + \sum_{k=1}^{3} PT(i,k) + CLP(i,1) + \sum_{k=1}^{8} HEC(i,k) + \sum_{k=1}^{384} UserCell\ (i,k) + \sum_{k=1}^{16} PED(i,k) \right)$$

Appendix C

Conference Papers Derived from this Research

This appendix presents the references of the two conference papers where preliminary results about the rural telephony by satellite research carried over the previous two years (1998 – 1999).

R. Conte, T. Pratt, "Remote and Rural Telephony through Hybrid Terrestrial Wireless and Satellite Networks”, *3rd Wireless Communications Conference IMAPS-WCC’98 proceedings*, pp.69-74, November 1998, San Diego, Ca.

R. Conte, T. Pratt, “Rural Telephony Performance with Wireless and Satellite Networks”, *Proceeding of the 2nd IEEE-UCSD Conference on Wireless Communications*, pp.21-26, Feb. 28 - March 2, 1999, San Diego, Ca.

Vita

Roberto Conte

Roberto Conte was born in Torreón,Coahuila, Mexico. He obtained the Electronics and Communications Engineering degree from the Universidad Autónoma de Nuevo Leon in Monterrey, Mexico, in 1986, and the Master of Science in Electronics and Telecommunications degree from Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE Research Center) in Ensenada, Baja California, Mexico in 1988.

Since 1988 he has been an Assistant Researcher in the Electronics and Telecommunications Department at CICESE Research Center. His academic assignments include teaching Analog and Digital Communications, Satellite Communications and Communications Systems Design at both undergraduate and graduate levels, in Mexico as well as in the U.S.

His research assignments have been mainly in the study of digital microwave radios as well as fixed and mobile satellite communications systems for both urban and rural applications. He was project leader in the development of the telemetry and communications subsystems for SATEX 1, a Mexican federal government financed micro-satellite.

Since 1996 he has been on educational leave at Virginia Polytechnic Institute and State University, Blacksburg, Virginia, working towards his doctoral degree as a Fulbright scholar, sponsored by Mexico’s Consejo Nacional de Ciencia y Tecnlogía (CONACyT).

His research interests include satellite and terrestrial wireless communications networks, broadband communications and communications networks design.

The author is a member of the Phi Beta Delta honor society, the IEEE Communications Society and the IMAPS Microelectronics Society. He is also a former President of the Latin American and Iberic Graduate Student Association at Virginia Tech, as well as International Student Representative at Virginia Tech’s University Council for International Programs.