Assessing the Technical, Economic and Policy-centered Feasibility of a Proposed Satellite Communication System for the Developing World

by

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Abstract

Satellite communication systems remain one of the most under utilized development mediums in less industrialized countries. This research proposes to establish a low cost satellite communications system tailored specifically for the developing world (+/- 30° latitude). The technical, economic and policy related frontiers of the problem are integrated within a MATLAB based satellite communication constellation simulation which is used to assess the feasibility of the proposed satellite system. The analysis demonstrates that with technical advances that would allow higher capacity systems at lower costs and a renewed policy framework in line with the present state of the satellite system industry, it could be feasible to establish a low earth orbit satellite communications system for the developing world.

The inputs to the satellite simulation are the proposed system's desired design variables and other relevant parameters. The outputs are system performance, capacity and cost. The Pareto optimal solution trade space is generated by the simulation model using a full-factorial run that probes the entire design space. The application of choice is short messaging services (SMS), chosen for its ability to provide proven connectivity at moderate costs. The capacity and cost of the most ideal Pareto architecture is contrasted against demand in the defined developing world region. The simulation also accounts for the necessary policy considerations and assesses the feasibility of the proposed system amidst the existing industry policy and regulatory framework. Additionally, data regarding the current economic standing of the region and how this forms an underlying basis for the digital divide is presented and assessed.

The policy and regulatory constraints on the acceleration of telecommunications development throughout the developing world are discussed. This thesis elaborates upon the need for a focus on design for affordability if satellite communication systems are to realize their immense potential for the delivery of needed social services to the world's marginalized.

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Nomenclature

Acronyms

FCC	Federal Communications Commission
GEO	Geosynchronous Equatorial Orbit
ICT	Information and Communication Technologies
ISO	International Satellite Organization
ITU	International Telecommunication Union
LCC	Life-Cycle Cost
LDC	Least Developed Countries
LEO	Low Earth Orbit
MF-CDMA	Multiple Frequency – Code Division Multiple Access
MF-TDMA	Multiple Frequency – Time Division Multiple Access
MOU	Memorandum of Understanding
MSDO	Multidisciplinary System Design Optimization
VSATS	Very small aperture terminals

Symbols

Design Variables

1. c	Constellation type
2. h	Altitude
3. ε	Minimum elevation angle
4. di	Diversity
5. P_t	Satellite transmit power
6. $G_t dB$	Satellite antenna edge cell spot beam gain
7. ISL	Inter-satellite link
8. MAS	Multiple Access Scheme
9. T_{sat}	Satellite lifetime

Constants

1. AKM	Apogee kick motor type
2. $AKMI_{sp}$	Apogee kick motor specific impulse

3. $StationI_{sp}$	Station keeping specific impulse
4. *MS*	Modulation scheme
5. *ROF*	Nyquist filter roll-off factor
6. *CS*	Cluster size
7. *NUIF*	Neighboring user interference factor
8. R_c	Convolutional coding code rate
9. *K*	Convolutional coding constraint length
10. R_{ISL}	Inter satellite link data rate
11. G_edB	Gain of user terminal antenna
12. P_e	User terminal power
13. *IDT*	Initial development time

Policy Constraints

1. FB_{up}	Uplink frequency bandwidth
2. FB_{down}	Downlink frequency bandwidth
3. *FLV*	Foreign launch vehicle

Objectives

1. $R_{lifetime}$	Total lifetime data flow
2. N_{users}	Number of simultaneous users
3. LCC	Life-cycle cost
4. N_{year}	Average annual subscribers
5. T_{total}	Total airtime
6. CPF	Cost per function

Benchmarking Metrics

1. N_{sat}	Number of satellites
2. N_{users}	Number of simultaneous users
3. LCC	Life-cycle cost
4. M_{sat}	Satellite mass
5. N_{cell}	Number of cells
6. T_{orbit}	Orbital period
7. $EIRP$	Satellite transmit average EIRP

8. $N_{gateway}$	Number of gateways

Requirements

1. BER	Bit error rate
2. R_{user}	User data rate
3. $Margin$	Link margin

Key Definitions

Pareto optimality	If the objective $\mathbf{J}^*$ of a design vector $\mathbf{x}^*$ is not dominated by any other objective in the objective space, then $\mathbf{x}^*$ represents a Pareto optimal design. Let $\mathbf{J}^1$ and $\mathbf{J}^2$ be two different objective vectors in the same objective space S. In the case of maximization, $\mathbf{J}^1$ dominates $\mathbf{J}^2$ if and only if (iff): $J_i^1 \geq J_i^2 \ \forall i$ and $J_i^1 > J_i^2$ for at least one i A design $\mathbf{x}^* \in$ S is Pareto optimal iff its objective vector $\mathbf{J}(\mathbf{x}^*)$ is non-dominated by the objective vectors of all the other designs in S. In other words, in optimization literature, design $\mathbf{x}^*$ is 'non-dominated' if it is impossible to move feasibly from it to increase an objective without decreasing at least one of the other objectives. Note that $\mathbf{x}^*$ only approximates a Pareto optimal solution, due to the way in which the design problem has been transformed into a combinatorial problem. But for the purpose of finding near-Pareto optimal solutions in the design space of this research, this difference can be ignored. [deW03]
Low Earth Orbit	A LEO communication satellite constellation system is a constellation of satellites that orbit the Earth at an altitude of about 500-1500 km and provide wireless communications between terminals on the ground. There are two major types of constellations: Polar and Walker. Both constellations are designed to provide the most efficient global coverage by using a minimum number of satellites, each with its own advantages and disadvantages.
MF-CDMA	Multiple Frequency – Code Division Multiple Access. Using a

	unique pseudorandom noise (PN) code, a code division multiple access (CDMA) transmitting station spreads the signal in a bandwidth which is wider than necessary. Each authorized receiving station must have the identical PN code to retrieve the information. Other channels can operate simultaneously within the same frequency spectrum as long as different, orthogonal codes are used. In MF-CDMA, multiple CDMA carriers at different frequencies are used to increase the number of channels.
MF-TDMA	Multiple Frequency – Time Division Multiple Access. In MF-TDMA, a communication channel simultaneously occupies a specific time slot in the time domain and a specific frequency carrier in the frequency domain. Thus the total number of channels is the product of the number of time slots and the number of frequency channels. Both the time domain and the frequency domain are used efficiently.
Trade space	The trade space includes the design and objective space. The term "design space" refers to the **x**-space, i.e. the domain of design variables where designers have formulation freedom. The term "objective space" refers exclusively to the **J**-space, i.e. the space of system attributes, behaviors or objectives that are used by decision makers to understand the resulting system designs. The term "trade space" is the umbrella term that encompasses both the design space and the objective space.

All definitions taken from [DC04] and [deWDC03a].

Chapter 1

Introduction

1.1. Overview of the Study

There are currently stark inequities in levels of accessibility to all of today's major social needs upon which a society's stability and by extension the world's stability rests. Some of the most pressing social needs surround sanitation, health, land, education, emergency relief, early warning systems, opportunities for involvement in the civic process, transport, jobs and rural connectivity to the outside world. A vital and potent vehicle towards addressing most of these social needs would be to strengthen the link between the potential and current reach of information and communication technologies (ICTs). Towards this end, this thesis proposes the establishment of a satellite communication system tailored specifically towards least developed countries (LDCs). This system would provide the low cost and potent communication application of short messaging services.

Economic analysis illustrated within this thesis provides a rationale for the decision to demarcate the equatorial zonal range of +/- 30° latitude as the developing world region of focus for the proposed satellite system. The definition is appropriate because as illustrated later in this thesis, 91.5 percent of the world's inhabitants within this equatorial range exist on a GDP per capita less than the world's average GDP/capita of $7,600 in 2002 dollars. This proposition of a satellite communication system for the developing world raises a plethora of engineering and design research questions that cannot be appropriately and comprehensively addressed without conducting an assessment of the economic, political, cultural and policy environment in which the technology will be implemented.

The present major impediments towards the growth of satellite communications as a tool to affect empowerment in developing regions are its impairing cost and an often non-facilitating policy and regulatory climate. However if the cost of satellite communications applications were commensurate with what people in less industrialized countries could afford, the technology could provide extremely needed instantaneous and universally available connectivity to a wide expanse of developing regions. This connectivity could 'leap-frog' many less industrialized countries to realizing needed access to the previously mentioned social needs. In regards to the policy realm, the field has noticed positive signs towards liberation of the telecommunication market in many developed and developing countries. A commitment to further encouraging telecommunications liberalization must be garnered from organizations such as the ITU and FCC to reduce barriers to entry and other existing debilitating facets of telecommunications policy.

This thesis shows that with a design for affordability revolution in the way satellite systems are engineered, coupled with the availability of low cost end-user terminals, significant achievements can be accomplished. Low cost applications can be provided that are in tandem with amounts the inhabitants of the demarcated equatorial range can afford to spend on communications services. To assess the feasibility of the proposed system a low earth orbit satellite communication system simulation is employed. This study researches whether there is a feasible satellite system architecture for the proposed system from the subset of non-dominated architectures resulting from the simulation utilized. The inputs to this MATLAB based simulation are, inter alia, the end-user's technical requirements for the system and the existing policy constraints on the system. After analysis, the simulation then outputs the orbital dynamics and physical attributes of the satellite system and information related to the system performance, lifecycle cost and capacity. The cost per function or in this case the cost per "message," along with the cost of the end-user terminal is also outputted from the simulation.

The costs to be born by the consumer are contrasted against researched amounts that people in this demarcated region can afford to spend on communications services. In the final analysis, after due consideration of the attendant technical, economic and policy related relevant concerns and changes necessary to realize the envisioned connectivity goals, the feasibility of the proposed system is evaluated.

1.2 Historical Background of the Study

In undertaking an analysis of this nature it is important to first have a keen understanding of the role information and communication technologies (ICTs) can play in the social development of a society. In any society an increase in the volume of information that can be exchanged is traditionally designated as progress. The milestones of this progress are earmarked by the emergence of new methods of transmission and analysis of information.

Unsurprisingly, the invention of printing i.e. the mobile typescript is often associated with the beginning of the Modern Era. A significant advancement was made at the beginning of the 20th century with the transmission of information using a radio-electric wave. This innovation in turn facilitated an increased reliance on the electromagnetic signal for data processing and transmission. These advancements played a major role in ushering in the technological revolution which dominated the twentieth century and continues to be a leading force in the twenty-first century. The 20th and now 21st centuries have been revolutionized by the information revolution much like the industrial revolution, brought about by the discovery of the steam engine, dominated the 19th century.

Satellite communications continues to play a major role in this revolution as it provides a robust solution to the problem of finding the best means to send a signal from one point of the earth to another. Before the emergence of satellite technology the only means to send a signal over long distances was to maneuver it from point to point overground via cables of radio-relay systems. With the launching of the first satellite in 1957 a new method for setting up a relay visible simultaneously from two distant points emerged. This idea was continuously exploited starting with the launch of the Telstar satellite in 1962.

A number of important factors led to the development and diversification of satellite communications in the course of the last fifty years. Firstly, satellite communication systems have the flexibility of not being limited to the terrestrial infrastructural needs of land-based communication systems. Secondly, people began to appreciate that the emergence of satellites can do away with existing bottlenecks such as the time and volume restrictions on the relay of intercontinental data. Thus with a foundation of significant benefits, the satellite communication field has continued to grow from strength to strength.

Today's global information infrastructure tends by and large to the elite and serves to widen an ever yawning divide between the haves and the have nots. The developing world is currently in dire need of communication mediums that can bridge this ever widening digital divide. In the developed world satellite communication applications are viewed as "substitution" applications, in such regions the system symbolizes a medium providing already available applications. However for many regions of the developing world where other means of communication (such as roads, post or fixed-line phones) are poor or non-existent, the presence of satellite communications connectivity would provide a means to the desired end of the provision of basic social needs.

The provision of this connectivity would be a significant empowering force as marginalized peoples can quickly find ingenious applications to forward their development agenda. There are numerous noteworthy examples of such ingenious applications. "Telephone Ladies" in Bangladesh have made a business from sharing and renting out mobile phones they bought using micro-credit loans. In Kenya, in order to get the best price for their harvest, or to ensure that the "middle man" is representing an accurate picture of the market, farmers and fishermen use mobile phones to conduct price comparisons from several markets. [ITU04] A means of connectivity can prevent wasted journeys. As a result, throughout Africa, small businesses use mobile units to find the cheapest vendor for supplies. In Zambia and several other African countries mobile phones are used to make cashless payments, this has significant economic and security benefits. [ECON05b] In Zambia's Soweto market located in the capital city, a Coca-Cola distributor's full load of bottles is sold every few days. A full load costs 10 million kwacha (about US$2000) in 2005 dollars. In cash, this amount is difficult to store discreetly, is a challenge to be counted and is valued at ten times the average Zambian annual wage, which makes it prone to theft. A system was thus implemented to have the Coca-Cola distributors pay for their deliveries not in cash but by sending a text message. [ECON05a] Other budding entrepreneurs have established themselves as "text message interpreters," wherein these interpreters send and receive text messages on behalf of their customers who may be illiterate or unable to afford the SMS end user terminal. It can thus be seen that this sort of connectivity reduces transaction costs, widens trade networks, facilitates real time feedback on the market price of often perishable goods and can reduce the need to travel. For various sectors of society in developing regions these benefits signal significant advancements towards economic development.

Over forty percent of the world's 6.3 billion people live in rural and remote areas of developing countries [WSRN], most in abject poverty. Their right to be able to communicate has not received much investment from the international technical and donor community. Statistics such as the island of Manhattan in N.Y. USA having more mobile phones than the entire continent of Africa stands testament to the disparities in access to the digital era across the globe. [ECON05] Mr. Iqbal Quadir, the developer of a very successful ICT for development initiative in Bangladesh known as Grameen Phone, once told a poignant personal story which illustrates the gravity of the aforementioned inequities. When Mr. Quadir was only about ten years old a family member was ill and his mother requested that he make the ten mile trip to decipher whether the village doctor was present and able to attend to the family's sick. This means of communication was the only option available to Iqbal's family as there was no other way this communication could be carried out other than physical discourse. Iqbal made the ten mile trip only to discover that the doctor was not in and had to make the ten mile return trip to deliver the bad news to his mother and his sick family member.

Unfortunately, lack of access to communication infrastructure and its attendant benefits is still grossly lacking in LDCs. This digital divide merits global concern as it can lead to national disintegration which not only limits the scope of a country's national economic growth but also risks political upheavals which would most certainly have international effects. [HM97]
The economic health of the developing world between 1990 and 2000 is the worst it has been since the Great Depression. [MW02] In Latin America for instance, income per person experienced a 75 percent growth rate between 1960 and 1980. However the next two decades would see income per person growing by 7 percent or remaining stagnant. Even more jolting economic statistics emanate from Africa which suffered reverse economic growth between 1960 and 1980 with a decline of some fifteen percent in income per person. Amidst all this China did register the fastest growth known to history between the 1980s and the turn of the millennium. Nonetheless, even including China which is weighted by its significant population of 1.3 billion, the developing economies as a group grew at half the rate between 1980 and 2000 as they had from 1960 to 1980.[1] Debilitating events such as the events of September 11, 2001 have not served to inject a positive change in this trend in the first 5 years of the 21st century. This poor economic growth over the past two and a half decades has only served to widen the digital divide. This puts in context the fact that the digital divide is symptomatic of deeper divides of at the very least – income, development and literacy.

The consequence of the aforementioned negative economic trend is that satellite communications applications have been out of reach economically for the people who could benefit the most. The last two major innovations in personal satellite communications systems, namely Iridium and Globalstar proved technological successes but economic failures. These systems had to file for bankruptcy as they proved too expensive an option even among affluent customers.

In trying to mitigate the digital divide it must be remembered that IT infrastructure introduced in a top-down manner is not the answer. For instance, placing a free computer in every household within a community in abject poverty does nothing if the recipients have no food or electricity and are illiterate. ICTs must be used as a tool to affect development, delivering sorely needed applications to empower, enrich and affect sustainable development.

1.3 Literature Search

1.3.1 Chang's Satellite Communication Constellation Simulation [DC04]

Chang in his June 2002 Master's of Science thesis developed a multi-objective, satellite communication constellation capable of incorporating technical, economic and policy-related factors. The simulation employs design space exploration, which facilitates assessing particular architecture in the larger technical, economic and policy context. A computer simulation captures the important elements of the satellite constellation design problem. The simulation maps high level design decisions such as the orbital altitude of the constellation or the transmitter power aboard the satellites to system performance, lifecycle cost and capacity. Chang's work makes a significant contribution to the understanding of engineering, economic and policy issues related to satellite communication systems and allows for the quantification of the impact of technological change and policy implementation on complex systems.

1.3.2 von Noorden's Analysis of Mobile Satellite Communications Applications for Developing Countries [WN89].

von Noorden illustrates examples of how a mobile satellite system can offer a range of applications and reach user communities that cannot be served by fixed systems. One potent application he expounds upon is using mobile satellite terminals as early warning systems. This has direct relevance to current times as it is now widely agreed inside and outside of the satellite communications industry that a greater prevalence of early warning systems could have assisted in abating the immense death toll of over 220,000 arising out of the December 26, 2004 Indian Ocean earthquake and tsunami. von Noorden identifies ways in which the International Maritime Satellite Organization's

(Inmarsat) satellite system could benefit the developed world. He rightly suggests that Inmarsat's institutional commitments, the evolution of space technology, and the introduction of new service applications will enable Inmarsat to contribute to economic and social developmental goals in developing regions.

von Noordon's suggestion that it is primarily economies of scale achievable through a global network which can put satellite communications within financial reach of most users in the developing world is not satisfactory to affect connectivity goals given the size of today's existing global income divide. Fifteen years on from this 1990 analysis, satellite communications has not been able to break the 'affordability barrier' for people in developing countries which leads to the conclusion that to truly make these systems tangible options for the people who could benefit the most, these systems have to be engineered for affordability from the design phase.

1.3.3 The ITU's Report on the Portable Internet as a Tool for Bridging the Digital Divide. [ITU04]

This report analyzes numerous case studies for which satellite communications acting in a symbiotic relationship with other ICTs has succeeded in providing communications access to marginalized peoples. There are examples emanating from Brazil, Canada, India, and the Caribbean. The Brazilian example is quite intriguing as it demonstrates the digital divide being bridged for a private nature reserve for which access is only possible via a 40 hour boat trip from the city of Manaus in Brazil. The reserve is known as the Xixuaú-Xiparinã Ecological Reserve. The reserve's isolation and lack of electricity has left the native Caboclo Indians with virtually no access to modern health care, education and economic opportunities.

To begin to address this problem, the first problem that had to be dealt with was a lack of electricity. To this end, the president of the Amazon Association contacted the Solar Electric Light Fund (SELF), a non-profit organization located in Washington, DC, for help with the financing and establishment of solar electric systems on the ecological reserve. SELF eventually installed the systems, which were used, inter alia, to power a satellite Internet link. High-speed Internet access (a maximum capacity of 4 Mbit/s downlink and a 192 kbit/s uplink) was established by means of a two-way VSAT system. To complement the VSAT system, a wireless LAN was implemented at the reserve. Before operation of the satellite dish commenced, it was necessary to acquire a licence from Anatel, Brazil's national telecommunications authority. No commercial return is expected from this venture. This connectivity has brought applications ranging from distance education, to telemedicine to e-commerce to this once cordoned-off reserve in Brazil. [ITU04]

1.3.4 The Economist's Report on Issues Behind the Digital Divide [ECON05b]

Jhunjhunwala argues that affordability is the "deciding factor" in determining whether the digital divide will be bridged. In light of this, he and his colleagues are researching a number of low-cost devices, including a remote banking machine and a fixed wireless system that cuts the cost of internet access by more than half. Jhunjhunwala is thus aware that creative research which designs for affordability commencing at the initial design phase is the direction research and development must focus on to affect tangible development goals.

1.3.5 Spectrum's Report on the Digital Access Index [SPEC04]

The ITU recently conducted a tangible measure of social inequities in the adoption of ICT across the globe. This measure is known as the Digital Access Index (DAI) and corresponds to a specific score for each country in the world which attempts to quantify the digital divide. The study was compiled by the ITU and released in November 2003. The ITU calculated a DAI ranking for each country which was determined by factors such as education, the affordability of Internet access, and the proportion of Internet users with high-speed connections, in addition to the raw availability of bandwidth. The factor that most illustrates the extent of the digital divide is affordability, defined by the cost of access to the Internet as a percentage of a country's gross national income per capita. The measure considered the basic monthly cost of Internet access for an individual line plus any additional cost for twenty hours online. The country ranking worst in affordability was the Congo which scored an alarming 5000 times worst than the country ranking the best. This speaks volumes to the astounding extent of today's digital divide.

The report illuminated other stark realities such as the fact that in Nigeria a year of internet access of the sort taken for granted by the developed world costs 3.54 times the average Nigerian's total annual income. This Digital Divide Index succeeds in quantifying the extent of today's digital divide as concerns internet connectivity, and without overtly stating it, vividly demonstrates that our understanding of and planning for the impact of communications satellites has lagged far behind the technical state of the art. That is, the link between the potential and reach of information and communication technologies broadly defined, remains dangerously weak.

1.3.6 Government of Jamaica's "E-Learning" Report detailing an E-learning project sponsored by the Government of Jamaica and the ITU. [ITU], [MOU03]

This report which details the general health of the Jamaican telecommunications industry, provides a vibrant example of the fact that despite the developing world's economic downturn in the last 25 years, encouraging "leap-frogging" effects are possible if connectivity means are provided at an affordable price to customers. First, it presents a summary of Jamaica's key macro economic indicators so that there is a context within which to judge the country's recent significant telecommunications growth. From Table 1.1 it can be seen that the Gross National Income per capita for Jamaica was a mere $2,820 in 2002 with a corresponding annual growth of a meager 1.0% in that year. These statistics rank Jamaica as a lower middle income developing country according to the ranking of the International Telecommunication Union. [ITU]

Jamaica Data Profile	
People	**2002**
Population, total	2.6 M
Population growth (annual %)	1.0
Life expectancy (years)	75.7
Fertility rate (births per woman)	2.3
Illiteracy total (% age 15 and over)	12.4
Illiteracy female (% age 15 and over)	8.6
Economy	
GNI (Atlas method) current US$	7.4 B
GNI per capita (Atlas method) current US$	2,820
GDP (current US$)	8.0 B
GDP growth (annual %)	1.0
GDP implicit price deflator (annual % growth)	7.1

Table 1.1: Summary of key macro economic indicators for Jamaica

In spite of these less than encouraging macro economic indicators, Table 1.2 shows the growth of the number of mobile and land line telephones in the four year period from 1999 to 2002. These numbers should be interpreted in the historical context that in 1999 significant regulatory reform took place in Jamaica's telecommunication industry. This reform saw Jamaica's incumbent telecommunications provider, 'Cable and Wireless', being forced to reduce the barriers to entry in the telecommunications sector which it had maintained at an impermeable level prior to the regulatory reform.

Phone Type	**1999**	**2000**	**2001**	**2002**
Land Lines	493,523	507,107	511,302	432,772
Mobile	117,861	249,842	640,453	1,187,293

Table 1.2: Number of mobile and land line telephones (1999 – 2002) [MOU03]

Table 1.2 indicates that in 2001 and 2002 the number of mobile phones largely outweighed the number of fixed public switched telephone network (PSTN) line phones in Jamaica. In fact in 2002, the number of mobile phones on the island was 1.2 million out of a total population of 2.6 million which is nearly 50%, further research indicates that the numbers have continued to rise. This pattern noted in Table 1.2 is largely due to the effects of deregulation ushered in by the liberalization of the telecommunication sector by the Jamaican Government just a few years prior to this 1999-2002 period.

Table 1.3 gives an idea of how the range of telecommunication services available in Jamaica has now flourished in this post monopoly-driven era within the telecommunications sector. It provides details of licenses issued by category of service providers between January 1, 2000 and October 31, 2003. Just fewer than three hundred licenses have been issued to service providers in ten categories since 2000. This represents a highly competitive telecommunications sector which could not have been realized had their not been regulatory reform.

Licenses	**TOTAL**
ISP	59
ISP (STVO)	7
IVSP	5
DC	26
DVSP	35
DSP	28
FTZC	10
FTZSP	8
IC	45
INT'L SP	35
TOTAL	**298**

Table 1.3: Number and type of telecommunications licenses issued (2000 – 2003)

Glossary for Table 1.3

DC – domestic carrier

DSP – Data Service Provider

FTZC – Free Trade Zone Center
FTZSP – Free Trade Zone Service Provider
IVSP – International Voice Service Provider
DVSP – Domestic Voice Service Provider
ISP – Internet Service Provider
ISP (STVO) – Internet Service Provider for Subscriber Television Operations
IC – International (Voice/Data/Transit) Carrier
INT'L ISP – International (Voice/Data) Service Provider

This Jamaican telecommunications case study is tangible proof of the fact that in developing countries people are willing and anxious even to incorporate the benefits of connectivity into their lives. With the amass of benefits connectivity can bring as detailed in the Historical Background section of this thesis, it is not of much surprise that people in poor countries spend a larger proportion of their income on telecommunications than those in rich ones. Providing these regions with *access* to connectivity thus makes sense on business and social good grounds for those who can provide this connectivity.

1.3.7 Digital Opportunity Initiative's (DOI) Report on Creating a Development Dynamic [DOI01]

The DOI, a public private partnership of Accenture, the Markle Foundation and the United Nations Development Program conducted a detailed analysis of the experiences of the deployment of ICT in a wide range of developing nations. The results of the study are presented in this report. The report concludes that the persistent debate regarding ICTs versus traditional development mediums is not the way the situation should be perceived. Rather the report found that ICTs appeared to be an integral component of development endeavors and have the potential to act as a powerful enabler of development. The report ends with a potent call to action for the international community to help developing countries in taking advantage of the potential of ICTs and integrating them into the core of their development initiatives.

The DOI report also details a rural connectivity case study which researched the Bangladeshi Grameen Phone initiative. In Bangladesh 97 percent of households and virtually all rural villages lack a telephone,[7] rendering the country one of the least wired in the world. This lack of connectivity has been a decisive factor in the underdevelopment of the country and the impoverishment of individual Bangladeshis. To address this problem Mr. Iqbal Quadir, a Bangladeshi native and lecturer at Harvard University's Kennedy School of Government co-founded Grameen Phone Ltd., a for-profit mobile carrier. He modeled what was an already existing system of women in the community purchasing cows with micro-credit loans financed by a familiar Bangladeshi Bank, Grameen Bank. Modeling off the animal husbandry model, where a mobile phone was now akin to a cow, the Grameen mobile phone system was set up to provide connectivity to urban areas and rural Bangladeshis.

Grameen Phone Limited is now the country's dominant mobile carrier. As of September 2000, Grameen Phone had 57 percent of the mobile telecommunications market in Bangladesh. Within rural areas, local entrepreneurs purchase phones with a micro-credit loan from Grameen Bank. Phone services are then sold at twice the wholesale rate to the village customers. An average of 70 customers a month use each shared village phone. When an incoming call is received on a shared village phone, the owner of the phone goes in search of the person who has been called and is subsequently paid for her services. This can become an inefficient means of receiving a call if the person who has been called is difficult to locate. This provides evidence for the need for personal communicator units for people especially in remote regions. Nonetheless, the results show that this Grameen Phone shared-access business model concentrates demand and engenders a relatively high cash flow allowing the phone owner to make his or her loan payments while still making a profit. Consequently, the rural telephones have turned out to be quite profitable for Grameen Phone resulting in revenues per phone of US$93 per month in March 2001. This insightful case study illustrates that it is possible to enable profitable, market-driven approaches to providing connectivity and its benefits even in the most rural of areas.

1.3.8 Lebeau's Analysis of the Development of Satellite Communications and its Socio-Economic Implications. [AL82]

Lebeau's 1982 analysis heralds the immense potential of satellite communications connectivity as a medium that can provide complete and instantaneous coverage of any given area. From a legal standpoint, the main problems of his time that Lebeau highlights relate to the allocation of frequencies to users and the limitation of broadcast reception to a specific national territory. He comments that overflow beyond national boundaries is much more difficult to confine than when terrestrial-based transmission facilities are used.

As far back as 1982 when this study was conducted and still today, the bottleneck restricting the development of terrestrial based connectivity is the cumbersomeness of the infrastructure necessary for full territorial coverage. These difficulties are exacerbated as the population density decreases (a predicament often referred to as the 'last mile problem') and/or the more mountainous the land. To make matters worst, often times developing countries do not have existing detailed maps of their own terrain adding another layer of difficulty to the non-ideal quest to provide connectivity solely by terrestrial means. Thus satellite communications must be a part of any time sensitive solution to address inequities in access to the information society.

Lebeau projects that there is a distinct correlation between gross national income per capita and quantitative indexes of the development of telecommunications in a given country such as the number of telephones per inhabitant. A correlation is not a causal relationship and the details of the causal relationships underlying the correlation are not easily modeled but research suggests that the causality is actually two way. Within this two way relationship, economic development fosters the growth of telecommunications and the development of telecommunications engenders economic growth. In light of these observations, Lebeau compares the emergence of satellite communications in less developed countries with the emergence of aviation in relation to land transportation.

The above analogy draws on some vivid correlations. In both cases, choosing the more 'sophisticated' option negates the need to create and maintain a ground system. This choice also facilitates operations being organized according to their level of priority, without the common obstacles that arise from the progressive development of a necessarily continuous system. The emergence of aviation now also means that travel that once looked long, tedious and very dangerous was now reduced to matter of hours with safety of travel increasing many-fold. Additionally, in contrast to satellite systems, a localized absence or failure of maintenance can disorient a major proportion of a terrestrial system, if not completely render it as inoperable. This fact is of extreme relevance to developing countries in which skilled manpower is not always available to provide maintenance and international consultants command costly salaries.

1.3.9 Mowlana's Analysis of the Political and Social Implications of Communications Satellite Applications in Developed and Developing Countries. [HM97]

Mowlana raises the important point that some people with genuine philanthropic objectives as concerns applying satellite communication technologies to the developing world fail in their initiatives due to lack of comprehensive forethought. This is due to a frequently occurring belief that one can simply transplant communications technologies in their existing state from industrialized countries to developing countries without trying to model it to the setting it will be operating within. Because the technology was not made with the developing world in mind, numerous problems can arise. If the system broadcasts content, such as television broadcasting, there could be fears of infiltration of the recipient's culture. There could also be concerns that the application provided by the system is not applicable to the proletariat's natural mode of going about their endeavors. And finally even if it is adaptable to the lifestyle of the developing country in question the 'unmodified direct transplantation' factor means it will most likely be unaffordable to the average person in the recipient developing country.

Mowlana contributes the keen observation that the potential of satellite communication technologies will not be realized unless participating nations succeed in agreeing on rules, procedures and policies that avoid technological and political conflict and allow the innovation to develop in an orderly and maximal way. He concedes that the growth of communications satellites is testament to some level of international cooperation, but reinforces that the current level of cooperation reflects only a fraction of that which will be necessary to foster and protect the growth of worldwide space communications in the future.

1.3.10 SpaceNews' report on Bringing Space Technology to the Developing World. [SPNS01]

The practical value of space technology was illuminated to Mazlan Othman, the director of the United Nations Office for Outer Space Affairs (UNOOSA) in 1997 when forest fires burnt more than 400,000 hectares in Malaysia and Indonesia, engulfing the entire region for weeks with thick, choking clouds of smoke. Although satellite imagery was available from developed nations, it was expensive and inadequate to assist her native Malaysia in fighting the forest fires. Othman explains that "we needed satellite photos of hot spots, but the accuracy initially available was only a resolution of 1 kilometer. That was insufficient and satellites with better resolution only came over Malaysia once every 20 days." Othman makes the key observation that "we realized that we could not rely on others for our specific needs." Since then, Malaysia has championed the development of a regional system of disaster monitoring satellites, a cause the UNOOSA supports.

Othman states that within Malaysia, while enough funds are not being allocated for research, there are concerted efforts to improve awareness among the public that if you want to build up the country in a bottom-up approach, space technology must be a part of the solution. A well informed conclusion is made that developing countries such as Malaysia need to build their own infrastructure (or have infrastructure built with their specific needs in mind) not only for the mere reason that owning your own technology is convenient but because it is sorely needed to solve the myriad of problems these regions face.

The UNOOSA director underlines the need to get private sector involved in this goal of bringing space technology to the developing world, stating that in contrast to the current conventional belief, there are incentives for the private sector be a part of the 'digital connectivity' solution. In detailing these benefits Othman reflects on the fact that there is a large group of countries that is still unaware of the many benefits of space technologies. However it is this very fact that means there is a lot of opportunity for industry to develop new markets. In these regions, the expanse of human capital having no other option for connectivity is immense and thus demand for communication services in these regions is at the highest levels. A commonly held myth is debunked when Othman states that it is not that these countries cannot afford space technology, it is that in many cases they are just not aware and thus have not built the necessary infrastructure they need to exploit the potential of space technology. Once this occurs the private sector can profitably sell communication services to developing regions.

1.3.11 Iida et al.'s proposition of a LEO Satellite Communications System for the Countries in the Low-Latitude Region. [TI94]

Iida et al. propose a satellite communications system using a non-inclined equatorial orbit for the +/- 20 degrees latitude equatorial range. This constellation is referred to as the Equatorial Zone Service Satellite System or EZ-SAT. Within this equatorial range the paper demonstrates that about 39 percent of the world's population would be serviced and that 56 percent of the world's countries would be within the demarcated coverage range of the EZ-SAT constellation. The resulting EZ-SAT system that Iida et al arrive at has nine satellites, with an altitude of 1264 km and 8 degrees of minimum elevation angle at the edge of the service area.

Iida et al demonstrate that their proposed system is not only simple and low-cost but would have immense utility due to both the significant fraction of the world's population it would service and the fact that the majority of these said people are marginalized peoples who could immeasurably benefit from the instantiation of such an endeavor. The authors conclude by imploring the satellite community to grasp the potential of satellite communications constellations to be significant landmarks along the path of development assistance to less industrialized countries.

1.3.12 Turner's Study of Constellation Design Using Walker Patterns. [AT02]

Turner discusses rules to guide in the selection of Walker patterns for new candidate constellations to provide earth coverage. Effort is placed on minimizing the number of orbital planes to allow for the establishment of constellations with a minimum number of launches, this is also a strong focus in Chang's satellite communications simulation. This 'minimum number of launches' objective minimizes the number of dedicated spares required for on orbit support and also allows for on-orbit servicing of satellites. Within his study Turner analyzes low-altitude, circular and high-altitude elliptical orbits.

Turner adds insight to the specific context of this thesis as he discusses low altitude partial coverage cases where coverage is not continuous but is maximized for a given zone of latitude. His work successfully shows that Walker patterns are of considerable use for constellation design under a variety of orbital conditions. This thesis utilizes a variant of Walker constellation design in the MATLAB based system simulation.

1.3.13 Lang's Analysis of Optimal Low Earth Orbit Constellations for Continuous Global Coverage. [TL93]

Lang contributes significantly to the field of low earth orbit constellations for continuous global or partial coverage. He developed an algorithm which allows the user to optimize non-polar, symmetric constellations of circular orbit satellites for continuous global or partial coverage. For constellations of T circular orbit satellites, the objective is to find the arrangement which necessitates the smallest value of the central angle radius of earth coverage, Θ, and still achieves the desired coverage.

Using Lang's algorithm within the developed simulation, symmetric constellations of satellites are produced in a tabular list format. Each constellation is defined with four values. Firstly there is the total number of satellites in the constellation, denoted by the letter 'T.' Secondly, there is the number of different orbital planes P; thirdly there is the relative phasing parameter F, and finally there is the common inclination of all satellites, I. T, P, F and I are then used to determine the central angle radius of earth coverage, Θ. These non-polar symmetric constellations are contrasted against the more traditional polar, non-symmetric constellations that Adams and Rider research in their reputed work in the satellite communications field. [WALR87] Lang found that the former were more efficient in many cases as they provided the required coverage with fewer satellites or with the same number of satellites at a lower altitude. Lang's algorithm is utilized in the partial coverage version of Darren Chang's simulation produced for the analysis in this thesis.

1.4 Open Questions

The literature search shows a lack of comprehensive quantifiable efforts undergone to design a satellite system that is affordable to those in developing regions. Allusions are made to possible cost reductions brought on by economies of scale but these are simply 'band-aid' solutions that are not likely to be effective and sustainable. Fundamentally, there needs to be a revolution from the design phase of such systems which I will henceforth refer to as 're-engineering' satellite system design. Within this 're-engineering', given economic data on what people are willing to pay for communication services and a concrete idea from those affected as to their priority needs, a satellite communications system established to meet these needs with affordability as a leading objective. The thesis sets about to address this open issue within the satellite communications sphere.

1.5 Needs Assessment for the Developing World

Table 1.4 presents a discussion of the identified needs of the developing world and projections of the role satellite communications can play in addressing these needs. When attempting to outline possible strategies to mitigate the needs outlined below it is important to remember that as Professor C.K. Prahalad from the Michigan Ross School of Business once said, it is important to cease thinking of the poor as victims or as a burden in need of 'handouts' that will keep them dependent on you. This insight is very analogous to the old adage that if you give a man a fish you provide him a single meal but if you teach a man to fish you would have fed him for life. Thus it is important to give homage to the fact that the poor are resilient and creative entrepreneurs and value-conscious consumers, which is what a human being has to be to survive on a very meager income. Analyzing the situation in this context makes a legitimate argument for the private sector to become strongly involved in satellite communications for development initiatives.

Identified Needs	**Solution**	**References**
Quality education	Distance education facilitated by broadband satellite communications	
Proper healthcare. There is a special need for certified practitioners across medical disciplines.	Telemedicine facilitated by broadband satellite communications.	
Clean water sources and proper sanitation	Utilization of satellites to identify clean water sources.	[DA04]
Food Monitoring	Ocean monitoring of fish levels and land monitoring of rice crops (for example), via satellite imagery.	[SPEC04]
Land	Utilization of satellite systems to provide detailed mapping of country's surface. This would provide details of land so decisions can be made as to its best use.	[CJ03]
Transport	Satellite communications applications reduce need	[ECON05]

	for transport as people can now call market, doctor, etc. instead of making drive or walk.	
Jobs	Adoption of the myriad of possible applications of satellite communication systems would necessitate a robust labor force to ensure the sustainability of the initiatives.	[ITU04]
Business market information (especially for informal commerce industry).	Sustainable e-business environment, satellite communications could provide means for internet connectivity for village craft makers and other members of the informal commerce industry to be able to make calls/send SMS to compare market prices for their produce.	[ITU04]
Increased access to the democratic process	E-Governance. Satellite communications can provide a medium which facilitates the civic involvement of the proletariat, for example, through "voting by SMS", which is already utilized in South Africa.	[ITU04]
Improved Maritime Communications	Maritime operations particularly off the coast of LDCs still suffer from the lack of communications and inadequate navigational aids. Satellite communications could extend the benefits of communications to even the simplest of fishermen.	[WN89]
Air traffic services	von Noorden reports that in LDCs pilots are frequently made to perform their own air traffic control in mid-air using vhf radio. The quality of air traffic control in many LDCs could be significantly improved through the utilization of satellite communications technology.	[WN89]
Emergency Relief	Satellites could be used to conduct detailed damage assessment and to help coordinate relief	[WN89]

	activities. Would provide much needed relief against broken or non-existent land communications systems.	
Early warning systems	Develop satellite communication systems as early warning systems for all major subdivisions of the globe.	[WN89]

Table 1.4: Developing world's identified needs and services that could address them

Table 1.4 unambiguously shows that that there exists a stark and burgeoning need for a myriad of services which satellite communications could facilitate. Some general pertinent issues that would need to be addressed in tandem with the above solutions are the development of an ICT Policy Framework for the different regions in the developing world (Latin America and the Caribbean, Africa, Asia, the Middle East). Obstacles to establishing appropriate infrastructural frameworks, connectivity & funding must also be identified and possible solutions outlined. Identifying resources for this bridging the digital divide initiative is imperative. The UN Office for Outer Space Affairs, the United Nations Development Program, the ITU and the European Development Fund are but a few international development organizations that could make serious inroads with respect to funding.

There is currently a dilemma of how to convince potential funders and developing world governments to allocate limited resources to ICT investment while basic needs are still to be fulfilled. Developing regions must be made aware of the fact that ICTs should not be thought of separate and apart from basic needs, but rather they should be viewed as vehicles through which the basic needs can be ascertained.

1.6 Motivation for Current Research

A serious bottom-up commitment needs to be given to the challenge of making satellite systems affordable for the regions that stand to benefit the most from the applications they bring. The approach cannot be to take an already established system, such as Iridium or Globalstar, which has been proven to be out of reach financially for developing economies and hope advertising or mass production strategies will bring it into the hands of the poor. In contrast, the industry must seek to re-engineer system design and if committed to bridging the digital divide then specific attempts must be made to design for affordability. A successful endeavor to achieve this goal must seek to quantify the analysis, be methodological and incorporate people's purchasing power into decisions on the type of application and its eventual cost. This change in design approach is fundamental as the cost to the consumer is the deciding factor in determining whether or not the digital divide will ever be bridged. It is this need to 're-engineer' satellite system design that motivates this study.

Currently, the link between the potential and current reach of communication technologies is very weak. The fact is that where there is no existing infrastructure, or where other forms of communication are not economically viable, satellite communications may be the only time sensitive solution. Connectivity using traditional terrestrial networks for rural or remote areas is a very lengthy and expensive process. Furthermore, the recent surge in China's demand for scrap metal has resulted in cases across the African continent of the poor uprooting traditional land lines to mine the copper casing and sell it to those willing to export it to countries such as China. Thus continuing to pour all of ICTs investment funds and research and development into exclusive traditional land based means of connectivity is an extremely inadequate way to move forward.

The developing world is thus in dire need of a medium that can extend access to communications for those in most need and which is not affected by the country's topology and state of infrastructural layout. There is also a need to create the regulatory and policy climate that will foster the growth of communication technologies within and across borders. At every step of the process there is a significant need for consideration to be given to whether or not the system will be economically viable and sustainable. Also, symbiotic connectivity with PSTN, fiber optics and other traditional means of communications should be the goal of satellite communications engineers. This should be especially so since there is not a need for expensive supporting infrastructure to make this symbiotic relationship a reality. Moreover there is a principal need for the technology to be unambitious and affordable.

In developed regions satellites will only experience continued need if they offer unrivalled competitive advantages, such as broadcasting and providing connectivity in deeply rural areas. Moreover, this research is motivated by the fact that for developing regions satellites would not be merely an alternative form of communication but would rapidly enhance development effectiveness and robustly address the needs detailed in the preceding paragraph. In the world's LDCs, the populace should be armed with a suite of space and land based connectivity mediums which first and foremostly hold the potential to significantly increase knowledge sharing and access to information which is a tried and proven means to sustainable development. There would also be the result of a general building of local capacity which would empower communities in numerous ways. This is also a principal motivation for this study.

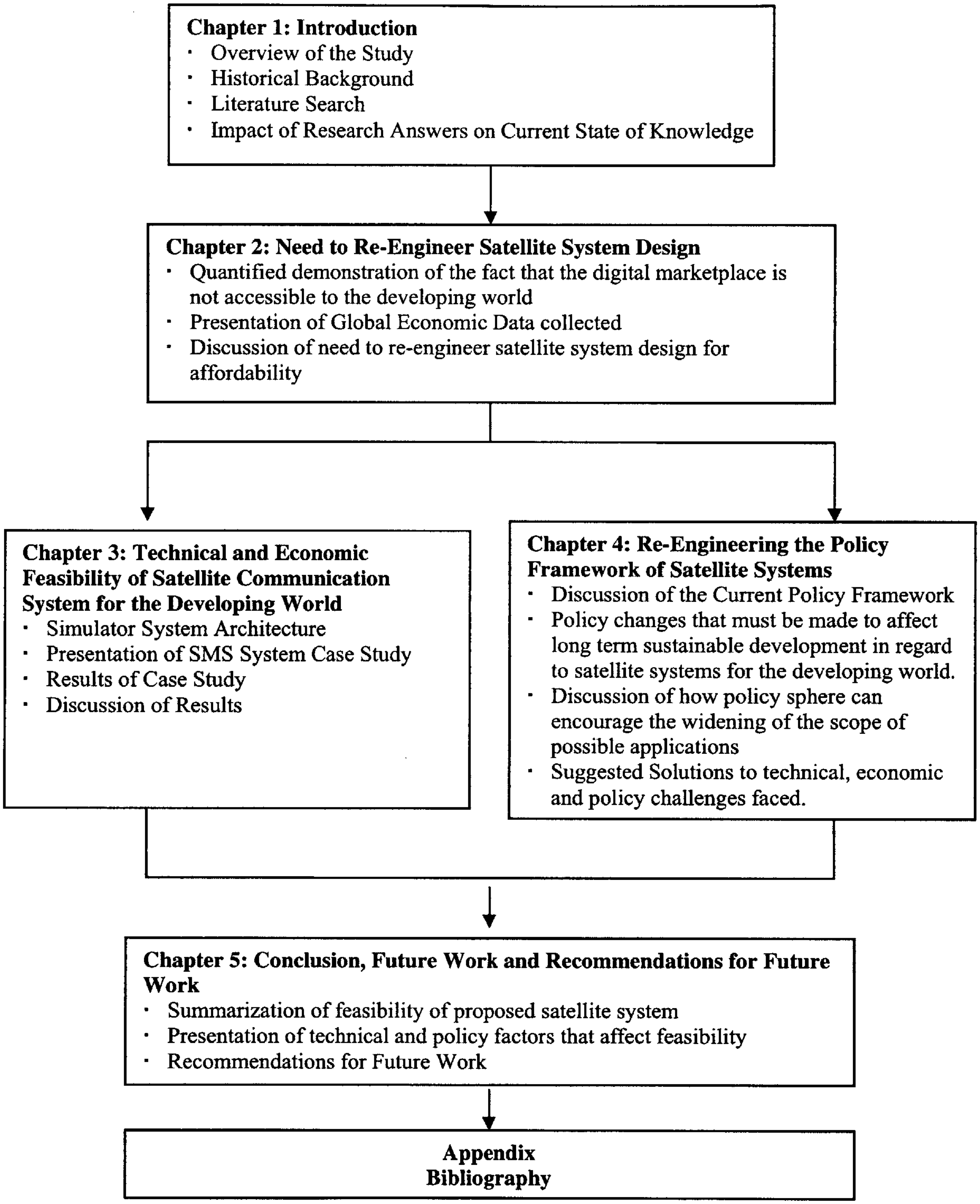
A solid example of the empowering effect of access to communications is provided through a new study by Leonard Waverman of the London Business School, and Meloria Meschi and Melvyn Fuss, of LECG, an economics consultancy, provides the most in depth analysis yet of the relationship between mobile phones and economic growth. Waverman and his colleagues used a technique called the endogenous growth model which is widely employed to investigate differences in growth rates between countries. They used this model to study the impact of telecoms on economic growth in 92 countries, both rich and poor between 1980 and 2003. Overall Waverman's research suggests that in a typical developing country, an increase of ten mobile phones per 100 inhabitants boosts gross domestic product growth by 0.6 percentage points [ECON05a]. This gives but a small window into the amazing development potential of any medium that can provide connectivity to regions that currently have no existing institutionalized means of communicating with themselves or their outside environs. To this end, the research hopes to play a major role in strengthening the aforementioned 'link' between the potential and current reach of satellite communications technologies.

1.7 Impact of Research Answers on Current State of Knowledge

This research employs a methodological and quantifiable approach to decipher the feasibility of the proposed satellite system, facilitated by the established satellite communications constellation simulation which models the technical, economic and policy frontiers of this feasibility study. The research impacts the current state of knowledge in the satellite communications for development realm by allowing for a detailed understanding of the technical, economic and policy factors that would enable a satellite communication system such as the one proposed by this thesis to strengthen the link between the current potential and reach of its technology.

The research allows for both a quantitative and qualitative understanding of how 're-engineering' satellite systems for affordability in both the technical and policy realms, can catapult satellite communications through the 'affordability barrier' for developing countries. Additionally, a thorough global economic analysis illuminates both the expanse of the income divide and the need for immediate action on this issue. Lastly, the policy and regulatory analysis impacts the current state of knowledge by shedding light on the policy and regulatory changes necessary to enact sustainable satellite communications for development growth in today's policy framework.

1.8 Thesis Preview



Chapter 1: Introduction
- Overview of the Study
- Historical Background
- Literature Search
- Impact of Research Answers on Current State of Knowledge

Chapter 2: Need to Re-Engineer Satellite System Design
- Quantified demonstration of the fact that the digital marketplace is not accessible to the developing world
- Presentation of Global Economic Data collected
- Discussion of need to re-engineer satellite system design for affordability

Chapter 3: Technical and Economic Feasibility of Satellite Communication System for the Developing World
- Simulator System Architecture
- Presentation of SMS System Case Study
- Results of Case Study
- Discussion of Results

Chapter 4: Re-Engineering the Policy Framework of Satellite Systems
- Discussion of the Current Policy Framework
- Policy changes that must be made to affect long term sustainable development in regard to satellite systems for the developing world.
- Discussion of how policy sphere can encourage the widening of the scope of possible applications
- Suggested Solutions to technical, economic and policy challenges faced.

Chapter 5: Conclusion, Future Work and Recommendations for Future Work
- Summarization of feasibility of proposed satellite system
- Presentation of technical and policy factors that affect feasibility
- Recommendations for Future Work

Appendix
Bibliography

Figure 1-1: Thesis Preview

Chapter 1 sets a framework for the research problem by firstly giving an overview of the study. The historical background of the problem is then detailed so an appropriate context can be had for the study. Work done thus far in this research regime is detailed through the presentation of the results of the literature study. Remaining open questions from this literature research are then presented to motivate the need for the present research. In light of the above, the motivation for the current research along with an analysis of the impact it will have on the current state of knowledge in the research sphere are then detailed.

Chapter 2 then presents solid evidence of the expanse of the digital divide which is largely based on an underlying income divide. The analysis in this Chapter makes the argument for why a re-engineering satellite system design for affordability revolution in satellite system constellation design is necessary for efforts to bridge the digital divide.

Chapter 3 analyzes the technical and economic feasibility of the proposed satellite communication system for the developing world. The analysis commences with a presentation of the details of the MATLAB based satellite communication simulation instantiation for this zonal equatorial coverage, proposed satellite system feasibility study. The details of the SMS version of the simulation are presented along with a presentation of how the feasibility analysis was carried out. The results of the case study along with a discussion of the implications of the results are then discussed.

Chapter 4 takes a detailed look at the "re-engineering" that needs to take place within the policy framework of satellite systems. Answers are proffered for questions such as: Is the current policy framework acting as an obstacle to the establishment of satellite systems for the developing world? What policy and/or regulatory existing schemas would be obstacles to establishing proposed satellite system? What policy changes need to be made to affect long term sustainable development in regard to satellite systems? How can current policy sphere encourage the widening of the scope of possible common satellite communications applications (such as telemedicine or tele-education)? The policy-centered, technical and economic challenges faced and suggested solutions to these challenges are then discussed.

Chapter 5 rounds off the thesis with a summarization of the points surrounding the feasibility of the proposed satellite system for the developing world. The technical and policy components of a revolution in satellite system design surrounding design for affordability are also summarized. Recommendations for future work are then presented.

1.9 Summary

The first task of this introductory Chapter was to present an overview of the research objective and method of approach. A historical background of the study was then given to set a context for how the research moves forward. Previous work conducted regarding the relevance of advances in telecommunications, (with a focus on satellite communication systems), for development is reviewed and analyzed. Remaining open questions in the research realm that will be probed by this thesis were then presented. This Chapter also looked at the question of the most pressing public policy needs in the developing world today and the role satellite communications can play in addressing these needs. Next, a discussion of the motivation for the research is presented and the impact the research answers will have on the current state of knowledge within the satellite communications for development sphere discussed. The Chapter closes with a succinct preview of the information presented throughout the thesis.

Chapter 2

The Need to Re-engineer Satellite System Design

2.1 Introduction

In this Chapter the framework and supporting data is provided to support the need to re-engineer satellite system design for affordability. The development goals of the international development arena around Information and Communication technologies (ICTs) in general are first presented to set a context for the analysis. Telecommunication means that currently exist to provide connectivity are then explored along with a discussion of the past and current commercial satellite system industry. Solid evidence of the expanse of the digital divide which is largely based on an underlying income divide is subsequently analyzed. Finally, the argument for why a re-engineering of satellite system design for affordability revolution is necessary to support efforts to bridge the digital divide is presented.

2.2 United Nation's World Summit on the Information Society Objectives

The United Nations (UN) envisioned the need for a Summit on the Information Society after taking stock of the immense effect and potential of the digital revolution. To affect a multi-stakeholder informed dialogue and subsequent action steps on the topic of the digital revolution it was decided to place a world Summit on the Information Society (WSIS) on the UN agenda. The first Summit occurred in Switzerland in December 2003 and the second Summit will take place in Tunisia in November 2005. At the first meeting of the WSIS a set of objectives were outlined that the UN and the greater development community intend to have in effect by 2015. These objectives of the WSIS are shown in Table 2.1.

OBJECTIVES OF THE WORLD SUMMIT ON THE INFORMATION SOCIETY

BY 2015 IT IS DESIRED TO:

a) connect villages with Information and Communication Technologies (ICTs) and establish community access points;

b) connect universities, colleges, secondary schools and primary schools with ICTs;

c) connect scientific and research centers with ICTs;

d) connect public libraries, cultural centers, museums, post offices and archives with ICTs;

e) connect health centers and hospitals with ICTs;

f) connect all local and central government departments and establish websites and email addresses;

g) adapt all primary and secondary school curricula to meet the challenges of the Information Society, taking into account national circumstances;

h) ensure that all of the World's population have access to television and radio services;

i) encourage the development of content and to put in place technical conditions in order to facilitate the presence and use of all World languages on the Internet;

Table 2.1: Objectives of the United Nation's World Summit on the Information Society

The UN and other leading development organizations have recognized that the digital revolution propelled by the growth of ICTs has fundamentally altered the way people think, behave, communicate and transact business. The need to make the most of ICTs is potently highlighted by the fact that this revolution has far reaching potential. This potential is evidenced for example by the carving out of new ways to educate people, administer health care and earn a livelihood. The digital revolution also affects the administration of societies at a national level, hence making for an even more urgent need to ensure the possibilities afforded by ICTs are exploited. The effect on the administration of countries is demonstrated by ICTs impacting both on the way governments administer their country's civic process and the access marginalized people have to this civic process. Finally, of great interest to the international development agenda is the fact that the digital revolution has also afforded faster global humanitarian aid response and a new platform for environmental protection.

Because satellite communications play a non-negligible role within the suite of ICTs that hold the potential to bridge the digital divide, the preceding arguments sum up to serious action being necessary to ensure satellite communications are affordable to the developing world so this technology can realize its full development potential.

2.3 Communication Means that Currently Exist to Provide Connectivity

As at the first five years of the 21st century, the current main means of telecommunication available to mankind are shown in Table 2.2.

PSTN with copper wires & other traditional terrestrial wired means of connectivity.	**Wireless Terrestrial Connectivity (e.g., Wi-Fi, Wi-Max and Cellular Mobile Connectivity)**
Underwater fiber optic cables	**Satellite Communications**

Table 2.2: Current main telecommunication mediums

From the four main communications facilitating genres illustrated in Table 2.2, satellite communications is inarguably a genre which is markedly under achieving its connectivity potential for the reasons detailed in Chapter 1. A significant reason behind this underutilization of satellite systems is that the telecommunications industry often considers these four mediums to be in competition. This approach results in the sum of the whole being less than the sum of the parts with respect to the maximum effect all four mediums could have. Consequently, in light of what people in the satellite industry consider to be competing means to achieve connectivity and given the non-trivial present cost-related deterrences to employing satellite communications applications, engineers and policy makers alike have ruled this medium out as a vital aspect of the solution to bridging the digital divide.

However, the fact that under the current telecommunications setting the vast majority of the world is not able to reap the benefits of their human right to be able to communicate and participate in the information society should not be ignored. This argument is strengthened by the fact that land based mediums alone cannot remedy the digital divide inequities in a time efficient manner. Thus rather than accepting the current cost structure and applications provided by satellite systems as fixed and hence eliminating it from the set of ICTs into which research and development is invested, research should center around how satellite communications can be re-engineered for affordability. If satellite communications becomes an affordable medium, rather than act in competition, it could act in a symbiotic relationship with the other communications mediums detailed in Table 2.2. This would facilitate the necessary participation in the global information space of sparsely populated and deeply rural areas. Thus in the satellite industry's forward thinking it is important to end the current telecommunications policy legacy in which real tensions exist between these four main communication means of Table 2.2

	Ghana/ Accra	Mexico/ Mexico	Puerto Rico/ San Juan	Nigeria/ Lagos*	Average
Total Population	21,029,853	106,202,903	3,957,988	156,468,571	71,914,829
Population of Capital	3,460,757	14,576,626	431,285	10,601,160	7,267,457
Area of Country (km^2)	238,538.00	1,967,138.00	9,104.00	923,768.00	784,637.00
Area of Capital (km^2)	3,685.00	21,461.00	136.23	3,345.00	7,156.81
% of pop in Capital	16.46	13.73	10.90	6.78	11.96
Capital's area as % of total area	1.54	1.09	1.50	0.36	1.12
density of Capital (persons/km^2)	939.15	679.21	3,171.21	3,169.26	1,989.71
density outside of Capital (persons/km^2)	74.81	47.09	393.26	158.48	168.41
% reduction in density	92.03	93.07	87.60	95.00	91.92

Table 2.3: Key factors relating to the density of capital cities vs. the surrounding areas for Ghana, Mexico, Puerto Rico and Nigeria [CIAWFB], [WG05]

Table 2.3 illustrates, inter alia, the population density of the capital of the countries Ghana, Mexico, Puerto Rico and Nigeria along with the density of the regions outside each capital. These countries represent a wide swath among countries within the +/- 30° latitude range. The four chosen countries range from small and earning less than the world average GDP/capita (Ghana) to being large and earning more than the world average GDP/capita (Mexico). Note that the world average GDP/capita is \$7600 in 2002 United States dollars. Further details about these classification regions are given in Figure 2-8.

	Wired	**Wireless**	**Satellite**
Capital	$0.13	$1.76	$7.14
Outside of the Capital	$1.48	$20.78	$7.14

Table 2.4: Costs to system operator for the provision of communication services

Table 2.4 details the cost per user per km squared to a system operator for the provision of communication services to a country with average characteristics as shown in the sixth column of Table 2.3. The cost to provide the service to the capital of the country vs. more rural areas is detailed. Three different means for the provision of communication services are detailed in Table 2.4. The first means is via a wired service such as PSTN, the second is via a wireless service such as a terrestrial mobile system and the third is via a satellite communications system. For the wired service, the cost per user per km squared is calculated with the cost representing the cost to lay a km of copper which is taken to be $250 in US 2005 dollars. The cost to provide wireless service is taken to be the cost of setting up a mobile tower which is assumed to be $3500 in this analysis. For satellites, the cost per user is taken to be the life-cycle cost of the system. The life-cycle cost of the satellite system in Table 2.4 is taken to be $580 million dollars serving a subscriber base of 81, 259, 200 people. These are the key factors of the satellite system that was established through this research in Chapter 3.

For a greater understanding of the lifecycle cost (LCC) of a satellite system, Larson and Wertz in their text indicate that the LCC can be broken down into three main phases. [WLJR99] There is the Research, Development, Test, and Evaluation phase including design, analysis, and test of breadboards, brassboards, prototypes and qualification units. This phase also incorporates prototype flight units and nonrecurring ground station costs. Then there is the Production phase which includes the cost of producing flight units and launching them. Then finally, there is the Operations and Support phase which is comprised of ongoing operations and maintenance costs, including spacecraft unit replacements. Replacement satellites and launches after the space system's initial operating capability has been established are also a part of this Operations and Support phase.

Insight can be gained from analyzing the cost to the communications system operator to provide communications services (these services are as detailed in Table 2.2) to the average of the values listed in Table 2.3 as detailed in Table 2.4. For the purposes of this analysis it is assumed that terrestrial means of connectivity are supported from a main trunk backbone which runs approximately equidistant from the northern and southern boundaries/coasts of the country in question. For terrestrial services the population density of a region is a significant factor as wires have to be laid from the main backbone to each customer. As the density of the population decreases the cost per user to the system operator increases as cost per user is given by the cost of providing the service divided by the population density of the region. This difference in costs is vividly demonstrated in Table 2.4

In contrast, with satellite systems the cost of establishing the system is independent of the density of the region and satellite systems do not incur further costs to add additional users to the system. The situation is drastically different for terrestrial systems. Observation of Table 2.3 illustrates the large changes in densities that occur when one goes from the capital of the country to the surrounding areas which would include a significant proportion of rural land mass. Table 2.4 demonstrates the costing that is a result of this change in density. Going from the city to the surrounding areas, the density changes for each of the countries in Table 2.3 are significant. As can be seen, the density reduces on the order of greater than 90% when going from the capital to less dense surrounding regions. Due to satellites' lack of dependence on density, compared to terrestrial means of providing similar 'unwired' services, satellites are the clear winner with costs per user of $7.14 as opposed to $20.78 with terrestrial mobile systems.

It is this important fact that makes satellite systems so necessary despite successes with terrestrial mobile connectivity. This significant reduction in the population density of countries when one goes from industrialized to less industrialized regions makes it very costly to terrestrial systems to provide connectivity to those in rural areas with very little existing architecture. However because the cost to establish and add users to a satellite system is independent of the population density of its coverage area, satellite systems must be looked upon as the vehicle to provide connectivity to the rural and cut off regions of countries for which the 'last mile problem' renders terrestrial connectivity either very expensive or entirely not possible, due to rough or unknown terrain for instance.

2.4 The Commercial Satellite Systems Industry

Significant advancements have been made within the realm of satellite communications constellation systems since the first operational communications satellites were launched into geosynchronous Earth orbit (GEO) in 1962 (TELSTAR and RELAY). These advancements include commercial intercontinental telephone service, television broadcasting, scientific missions, space shuttle operations, telemedicine applications, and distance learning applications. These applications signify immense development in the telecommunications arena, but what path did the satellite industry traverse to get to this point? Section 2.4.1 responds to this question.

2.4.1 How Did We Get To Where We Are Now?

As recently as 1980, the main aspect of telecommunications infrastructure in the industrialized world was the public switched telephone network (PSTN). PSTN systems facilitated mainly voice and some low bandwidth data signals such as telefax and elementary computer data traffic. Within industrialized countries these PSTN systems had grown steadily since the turn of the 20th century and around this time of 1980, no other communications means seemed poised to compete with this mode of communication. PSTN systems have the disadvantage however that they are limited to recipients that are able to connect directly to the public switched telephone network by wire. It is this fact that motivated communication engineers to look to alternate solutions to provide global communication coverage. At the turn of the 1980s, the only means to provide the desired global wireless communications coverage without having to take into consideration terrestrial infrastructure needs was through GEO satellites.

Three GEO satellites, separated by 120° in longitude and orbiting the earth at an altitude of 35,786 kilometers can facilitate total earth coverage below approximately 70° latitude. The initial system to provide satellite telephone service via a GEO constellation was INMARSAT. The system was primarily catered to marine users. As a result of the transmission distance from the GEO satellites to the end user, delays between GEO satellites and the ground are at least 120 milliseconds, such a delay is discernable in two-way voice communications. This transmission delay meant that the distance factor associated with GEO systems rendered 'smooth' personal communications difficult. Combined with losses along the transmission path and bulky and expensive terminals, GEO systems never succeeded in convincing the necessary market share of customers to employ their services for personal communications. Furthermore, their few customers came from a market base that had no other telecommunications choice and that was not price discriminatory - such as military personnel, mariners and certain research scientists working in remote places. This failure to generate the necessary market share meant GEO systems did not realize the reductions in cost of service expected from economies of scale. By the mid-1990s, the nominal cost of a GEO satellite was around \$100- \$200 million US dollars with launch costs at approximately \$50 million. [deWDC03a]

2.4.2 Current State of Commercial Satellite System Industry

2.4.2.1 The Emergence of Low Earth Orbit Systems

It had now become obvious that personal communications would not be possible without tackling the ominous GEO distance factor. This motivated a significant development within the satellite communications industry which resulted in Low Earth Orbit (LEO) Systems coming on stream. Presently, the majority of communications satellites exist within GEO orbit, however LEO systems play the leading role in the provision of personal communications applications. It should be noted however that recently the Thoraya satellite, developed by the United Arab Emirates' Thoraya Satellite Telecommunications Company has been able to provide cellular services from GEO due the presence of large mesh antennas.

LEO communication satellite constellation systems orbit the Earth at an altitude of about 500-1500 km and facilitate wireless communications between terminals on the ground. Only three LEO systems have been launched in the past, they are Orbcomm by Orbital Sciences, Iridium by Motorola, and Globalstar by Loral. A defining feature of LEO systems is that they entail many satellites (up to 66 with Globalstar) working in concert. The two main types of constellations are Polar and Walker systems as illustrated in Figure 2-1. Each type of constellation has its own advantages and disadvantages with Polar systems being better suited for coverage that needs to include the poles and Walker systems being best suited for complete global coverage below a certain latitude (such as +/-70° for Globalstar). Hence with an equal number of satellites, a Walker constellation enables a higher diversity than a polar constellation. Diversity is the average number of satellites in view at once to a user on the ground. The benefits of a high diversity are that the user enjoys a higher availability, fewer dropped connections and reduced multipath fading.

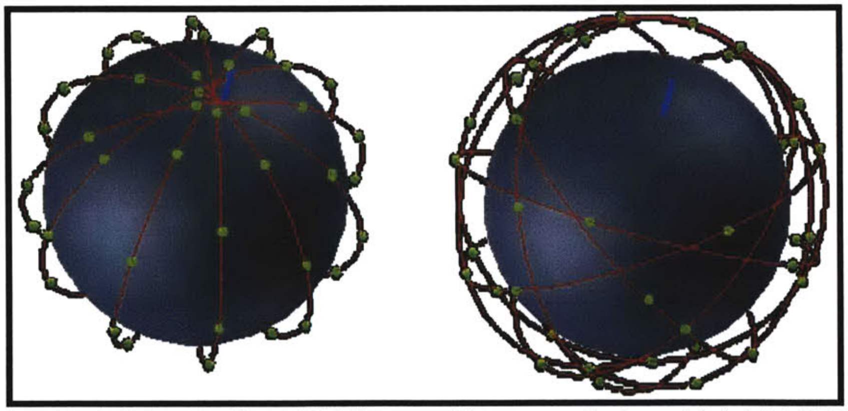


Figure 2-1: Polar (left) and Walker satellite constellations (right) [deWDC03a]

The general construct of a LEO communications constellation is shown in Figure 2-2. Ground users can be in the form of an end user terminal such as a 'satellite phone" or a gateway. Gateways allow communication between satellite phones and traditional wired PSTN land line telephones as illustrated in Figure 2-2. This connection between gateways and PSTN telephones is made possible by gateways having large antenna dishes and harboring a direct connection to the terrestrial PSTN system.

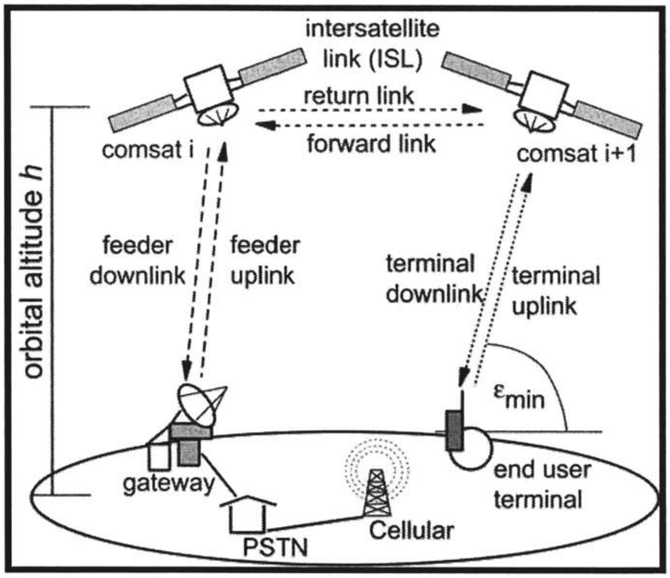


Figure 2-2: LEO communications satellite constellation. The orbital altitude, *h*, is typically between 500-1500 km. The minimum elevation angle, ε_{min}, is typically 5-15 degrees. [deWDC03a]

With the advent of LEO systems the distance problem that made personal communications difficult with GEO systems was solved. Transmission delays in LEO systems are on the order of 10 milliseconds which makes practical personal communications possible. The price paid for reduction in transmission delays is a significant increase in the number of satellites needed. Dozens of satellites are needed to ensure continuous global coverage at between 500 and 1500 km. Another challenge is the footprint area of LEO satellites.

Compared to GEO systems more complex technical feats had to be conquered in order to make LEO satellite systems a reality. On average a LEO satellite travels from West to East at a speed of 7 km/second and depending on satellite altitude and the location of the user relative to the satellite's ground track, the satellite may be visible for between 7 and 20 minutes. Therefore calls with a duration of greater than 7 to 20 minutes have to be flawlessly switched over from one satellite to another. This switching requires complex and thus costly switching hardware and software. Additionally, many GEO satellites operate in a one-to-many broadcast mode in which there is a satellite acting as the single source of transmission and many receivers on the ground. In contrast, LEO systems operate in a two-way, many-to-many mode which demands greater frequency bandwidth as well as increased hardware and software complexity with regards to both the space and terrestrial aspects.

The technical challenges were impressively overcome and with the reduced distance factor, which reduces the demands on power and antenna size, LEO satellite phones are much more compact than their GEO predecessors, which allows them to be employed for personal communication purposes.

2.4.2.2 Reasons as to Economic Failure of Major Past Satellite Systems

While LEO system designers displayed extreme technological prowess they were not as sound economically. This is evidenced by the two major satellite systems, i.e. Iridium and Globalstar, eventually filing for Chapter 11 bankruptcy protection. The lesson was taught that more than ever, astute system architects must not only be versed in the technical aspects of their systems but must also have a strong familiarity with and context for the underlying economics and existing competing and non-competing alternatives to the application it is desired to provide. If any of these components of the system design process is missing, the system will prove unsustainable. Both major satellite systems faced bankruptcy due to a similar underlying fact – at the time Iridium and Globalstar were conceived, that is 1990 and 1991 respectively, in the face of available terrestrial alternatives available later in 1998 to 1999, Iridium and Globalstar were too expensive to gain the market share that would afford them a healthy economic base.

Iridium and Globalstar's predictions for their number of users, N_u, turned out to be severely overestimated. As an example, the number of users prediction for Iridium was 6,076,000 subscribers in 1990. [deWDC03a]. However in hindsight, this number severely overestimated the actual N_u. This overestimation came with a heavy price tag as N_u and A_u are two key variables that must be estimated with some accuracy as far as this is possible for any particular type of service. The overestimate was unfortunately exacerbated by the fact that by 1991 predictions that had been made for the number of terrestrial cellular subscribers had proven to be significantly underestimated. Figure 2-3 demonstrates market predictions in 1991 versus actual number of terrestrial cellular network subscribers in the USA for the 1991 to 2000 timeframe. The US forecast is the green leftmost bar in each group of bars, while the US actual number of terrestrial cellular subscribers is the blue rightmost bar in each group.

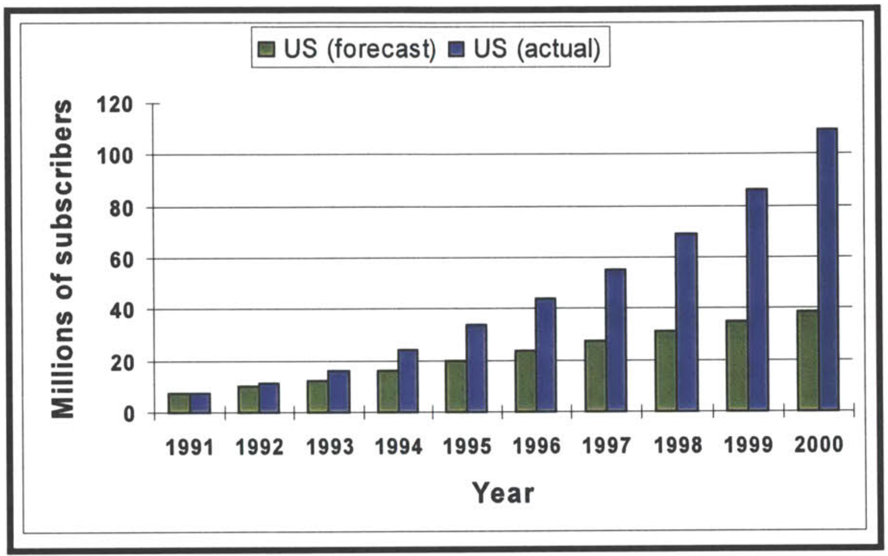


Figure 2-3: Market predictions (in 1991) versus actual number of terrestrial cellular network subscribers in the United States for the 1991-2000 period [deWDC03a]

Globalstar encountered a similar fate and it is this failure to fully understand their system's economic context that led to the system operators eventually filing for bankruptcy. Iridium filed a petition under Chapter 11 of the U.S. Bankruptcy Code in the U.S. Bankruptcy Court in Delaware in August 1999. Globalstar followed soon after with a similar bankruptcy petition in February 2002. [SAT]

2.4.3 Present Focus of Satellite Systems

With Globalstar having filed for bankruptcy only three years ago, satellite systems have yet to fully recover from the sizeable debt they incurred. In attempting to gain a comprehensive understanding of this economic breakdown in the satellite system industry, necessary insight can also be gained if one looks at satellite systems in general and seeks to understand exactly what type of customer the systems were targeted towards. A detailed analysis will show that the current focus of these satellite systems is primarily on the top niche business career professional whose career spans across countries and is in need of a means by which he can have a single satellite phone for instance that will work in any setting his travels dictate he work within. Hence the current design of the applications provided by satellite systems is mainly focused on design to push the technological frontier. This is especially so because often times because it is the top-niche customer in the industrialized world that is being catered to, there are an array of already existing options that the prospective customer could use to provide his connectivity.

Consequently, the satellite system designers must push the technological envelope to try to present an application that is technologically sophisticated, does more for the potential customer and could thus make him consider switching to the satellite based mode of connectivity. As Iridium and Globalstar proved however there are many other considerations to this problem and irrespective of the fact that the target market base did not tend to be very price discriminatory, a convincing argument for the prospective customers to switch to satellite based services was not delivered.

In contrast, were these satellite system designers to focus research and development efforts towards developing less technologically elaborate applications which provide basic connectivity and which are targeted towards the immense potential market base in the developing world, oversubscription, rather than heavy debt is likely to be the challenge incurred. It is with regards to this important point that satellite systems are being grossly under-utilized today, but the satellite industry will only be able to realize its full potential to bridge the digital divide if a revolution occurs in how satellite systems and the ensuing applications are engineered. Because affordability is the key factor, the systems have to be 're-engineered' for cost-effectiveness.

2.5 The Establishment of a World Database

2.5.1 Defining the Developing World

It is important that when proposing a satellite system to provide connectivity to the "developing world," that a defendable definition of the developing world is presented. For this thesis, it was desired to identify and subsequently have the proposed system address an equatorial belt that captured the world's poorest countries. In order to carry this analysis out a survey was done of GDP per capita vs. the latitudes of all the countries in the world as presented by the exhaustive U. S. Central Intelligence Agencies' world Factbook. [CIAWFB] The world Factbook details extensive up to date information on 229 of the world's countries. Information and local context is given for important factors relating to a country such as a concise history, its geography, people, government, economy, communications, transportation, religions, military and transnational issues. Using the information provided in the world Factbook an extensive database was put together to firstly get a working definition of the developing world and then to explore other key aspects of the developing world that would inform the development agenda of this thesis. A summary of the world database is shown in Appendix A.

As stated, with regards to the developing world definition, a graph was computed of GDP per capita vs. latitude for all the world's countries. The resulting graph is shown in Figure 2-4. The graph has somewhat of a basin shape. A rectangle ABCD is demarcated, wherein the length AB outlines the average world GDP/capita of $7600 in US 2002 dollars. As Figure 2-4 illustrates, the majority of countries within the +/- 30° latitude range have a GDP per capita less than that of the world's average. It is this keen observation that lends to the definition of the developing world for the analysis in this thesis being the equatorial range between 30° north and 30° south latitude.

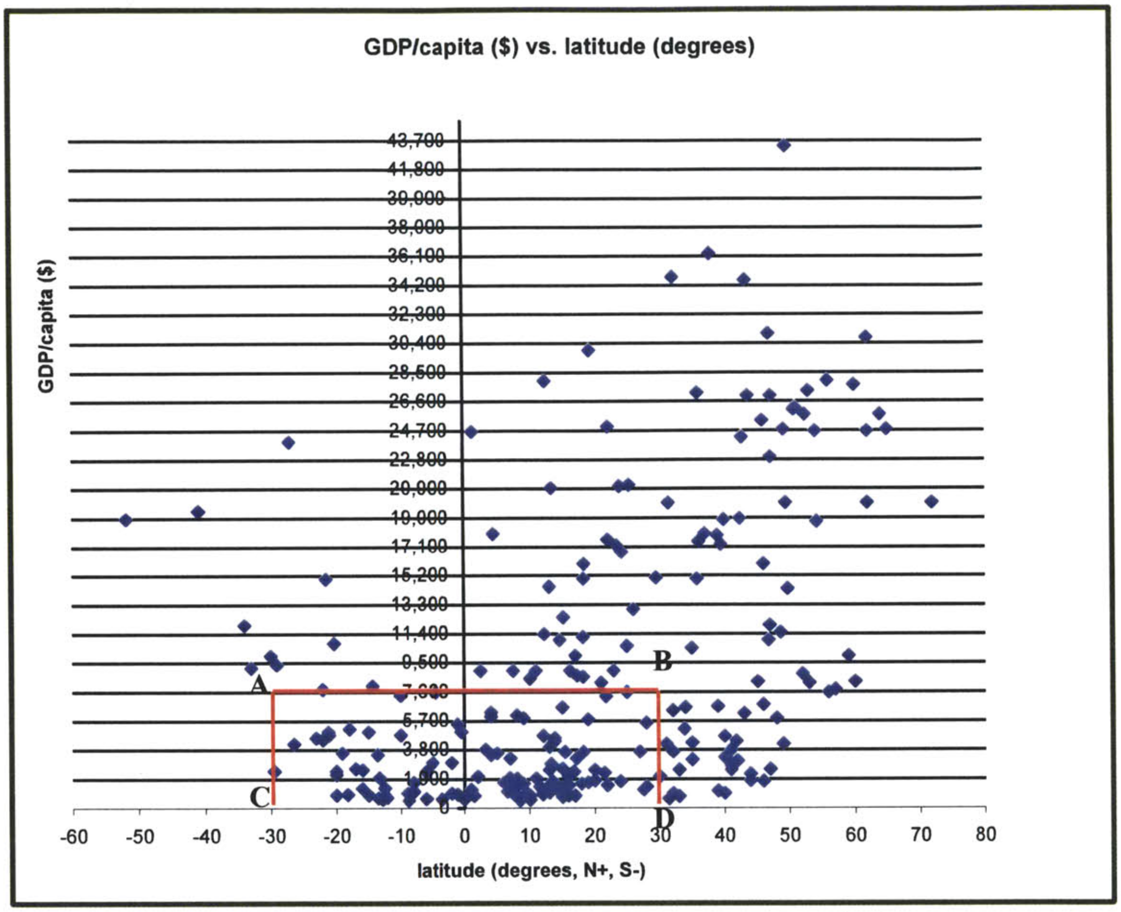


Figure 2-4: Global comparison of GDP/capita vs. Latitude

2.5.2 Further Insight Gleaned from Database Compilation

The economic data collected within the database shown in Appendix A demonstrates that as at 2003, 53% of the world's population resided in the +/- 30° latitudinal equatorial range. This fact is illustrated vividly in Figure 2-5 which shows a distribution of population sizes (where each country is represented by a circle in which its population size is proportional to the radius of the circle) against a latitude vs. longitude graph for all the world's countries. The +/- 30° latitude lines are demarcated by black arrows making it possible to deduce from simple visual analysis that at least 50% of the world's population inhabits this equatorial range.

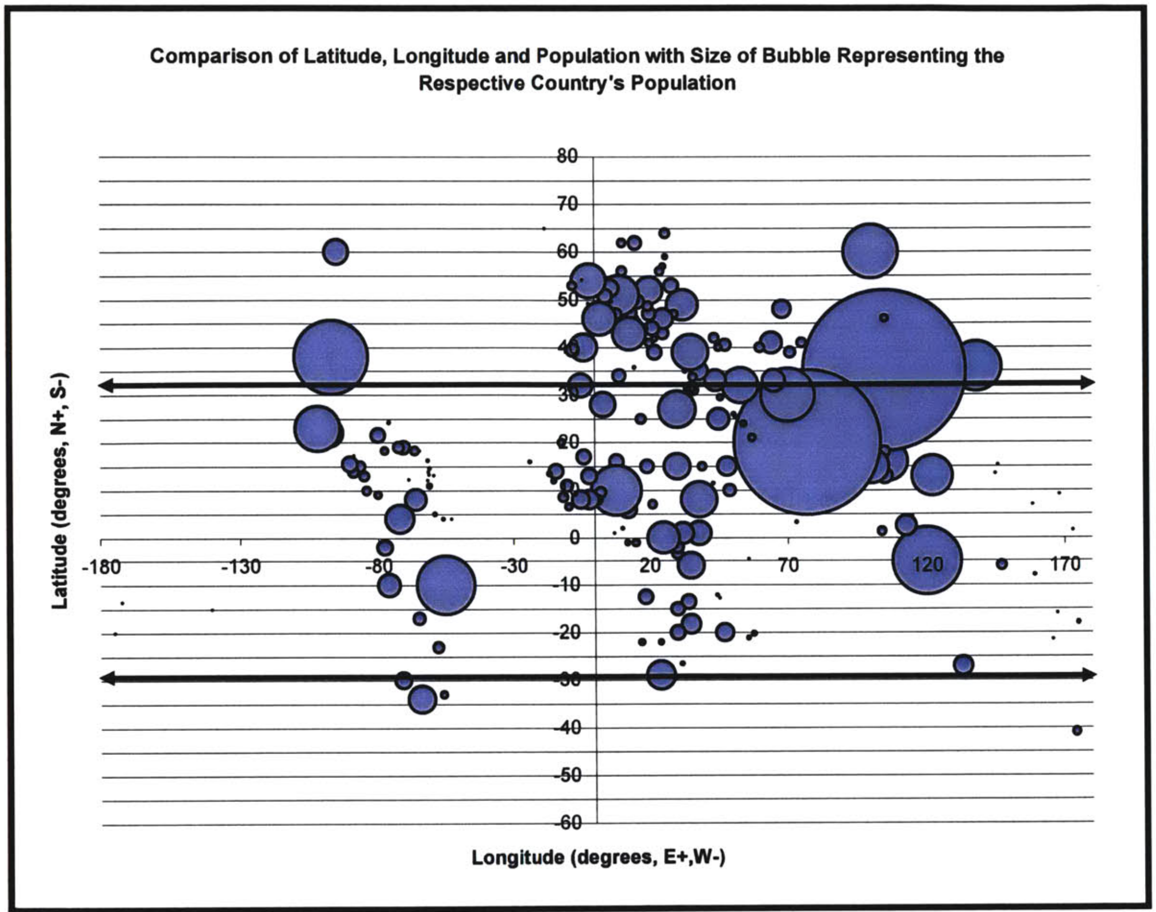


Figure 2-5: A Global 3-D comparison of Longitude, Latitude and Population. The population value is displayed as the size of the bubble marker.

Figure 2-6 in illustrating the population of each of the world's countries vs. latitude, allows an even more detailed analysis of the nature in which the world's population is laid out around the key +/- 30° latitudinal equatorial range. Note that in Figure 2-6 the y-axis shows the non-cumulative population of each country. Also the world's two most populous countries, China and India, with populations of 1,284,303,705 and 1,045,845,226 persons respectively as at 2003 and latitudes of 35 and 20 degrees north respectively, were not plotted in Figure 2-6 so that the information on the other countries could be viewed with clarity. Again, the point is made through this Figure that this thesis' equatorial range definition for the developing world does indeed account for a significant fraction of the world's population.

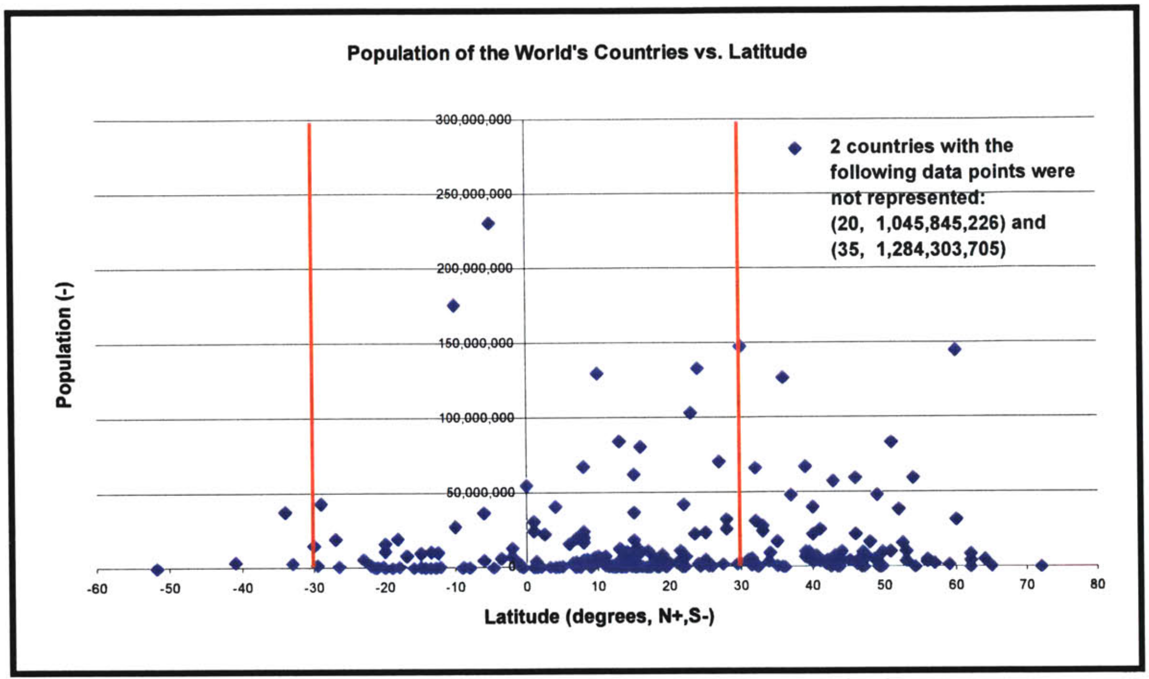


Figure 2-6: Global comparison of Population vs. Latitude

Figures 2-5 and 2-6 demonstrate how different countries compare when their population sizes are compared to their latitude and longitude and latitude only respectively, but is there insight to be gained from a comparison of population sizes to respective GDP per capitas? Most definitely; such an analysis would allow one to know the proportion of the world's population which earns less than the world's average GDP per capita, the magnitude of the fraction of the developing world having a GDP less than the world's average could certainly lend anchorage to the need to "re-engineer" satellite system design for affordability. Figure 2-7 plots population against GDP/capita for all the world's countries. The population y-axis is non-cumulative. A vertical line is drawn at the world's average GDP per capita of $7600 in 2002 dollars. This Figure shows a significant cluster of countries exist with GDP per capitas less than $7600.

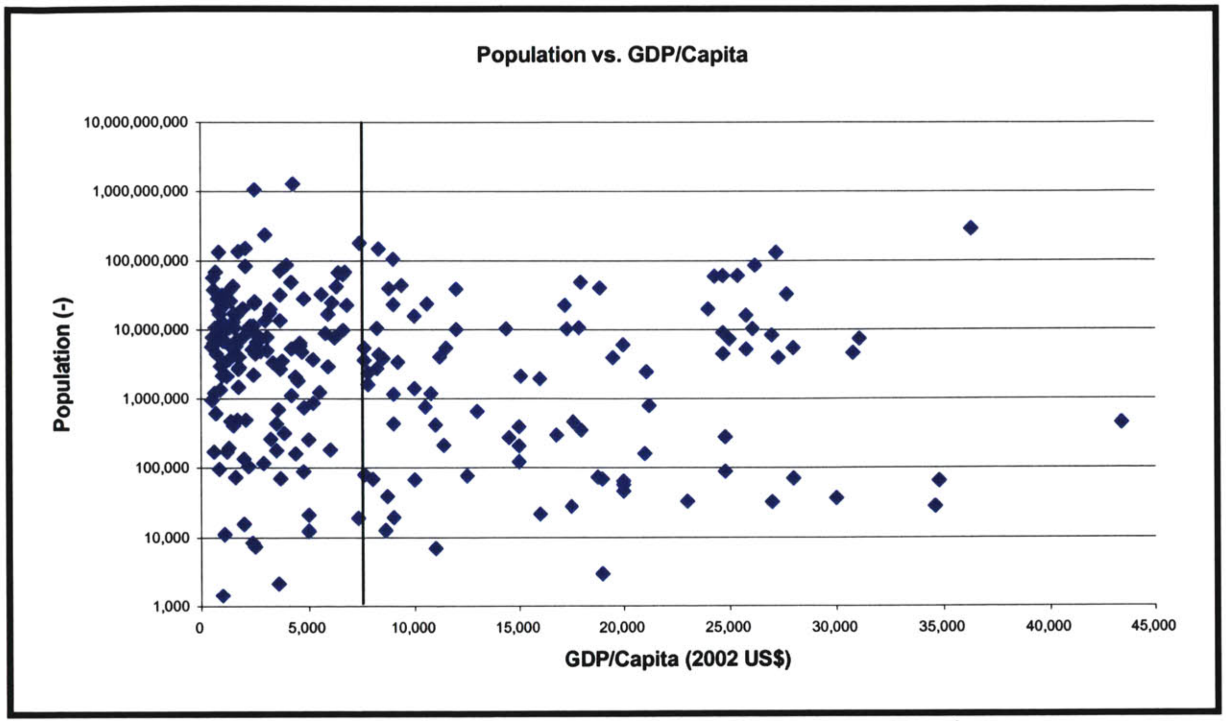


Figure 2-7: Global comparison of Population vs. GDP/capita

Figure 2-8 shows this relation even more vividly by differentiating between countries within the demarcated +/- 30 ° latitudinal range (red triangles) and countries which lie out of this range (blue diamonds). A vertical solid purple line demarcates the world's average GDP per capita of US $7600 in 2002 dollars and a dashed green line demarcates a country's average population as at 2003 of 27, 221, 930 people. Figure 2-8 shares many key insights. Firstly, as at 2003, the number of people in the +/- 30 ° developing world equatorial belt was approximately 3,318,842,429; the fraction of people within this developing world region that earn less than the world's average GDP per capita is 91.4% or 3,018,842,429 people. This staggering percentage of the developing world population illustrated by the red triangles is shown lying to the left of the world's average GDP per capita line. A visual analysis of the information presented in Figure 2-8 makes it easy to see that the majority of developing world countries earn less than the world's average GDP per capita. A second interesting insight brought out through the mode of representation of the population vs. GDP/capita analysis in this graph is that by using the world's average GDP per capita line and the average world Population line as points of reference, it was possible to break the graph up into 4 quadrants. These quarters entail countries which range from having GDP per capitas greater than the world's average and having smaller than average populations to entailing countries which have larger than the world's average population and GDP per capitas less than the world's average. Taking a look at the quarter in Figure 2-8 which is comprised of countries which have less than both the world's average population and the world's average GDP per capita, it is noteworthy that many of the developing countries that are already having to deal with economic constraints from having low GDPs also have small populations which often also means a smaller land mass or smaller domestic market potential. Being a small country can add other constraints of limited natural resources and infrastructure across the scope of a country's major necessities and it is this lack of basic infrastructure coupled with economic fragility.

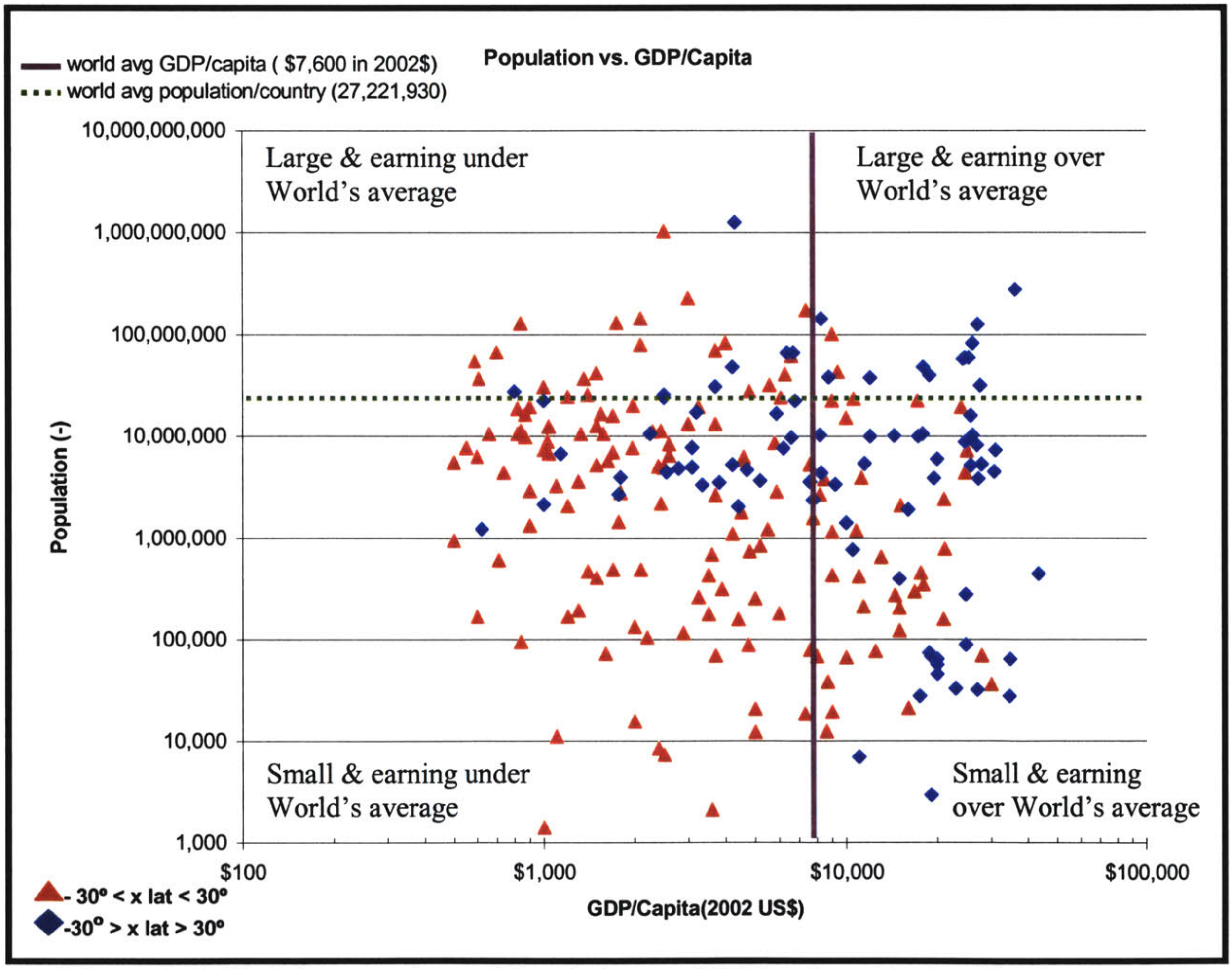


Figure 2-8: Global comparison of Population vs. GDP/capita with classifications

Figure 2-9 shows a final noteworthy insight gleaned from the compiled developing world database. It shows a graph displaying the cumulative population within the developing world on the y-axis wherein for any point on the graph that point represents the total population within the developing world which has a GDP/capita greater than or equal to the respective GDP/capita shown on the x axis. The data presented in this graph provides a greater understanding of the number of people in the developing world who have GDP/capitas greater than or equal to the world average. Specifically this number is highlighted by the horizontal line drawn which shows that only 300 million people or 8.6% of the developing world have a GDP/capita greater than or equal to the world average. This bears greatly on affordability considerations that should be kept in mind when designing services for this developing world region.

Another important fact to note is that as shown in Figure 2-9 there is a significant drop off in GDP/capita between $2000/year/person and $3000/year/person in 2002 US dollars. Approximately 2.23 billion people in the demarcated developing world region earn a GDP/capita greater than $2000/year/person. However there is a severe drop off when one moves to a GDP/capita of $3000/year/person as only 0.9 billion people earn more than this amount. Hence an increase in GDP/capita of only $1000/year/person caused a sizeable reduction in the number of people in the demarcated range that earn greater than or equal to that amount. Again, statistics such as these greatly underscore the need for design for affordability in satellite and end user terminal design.

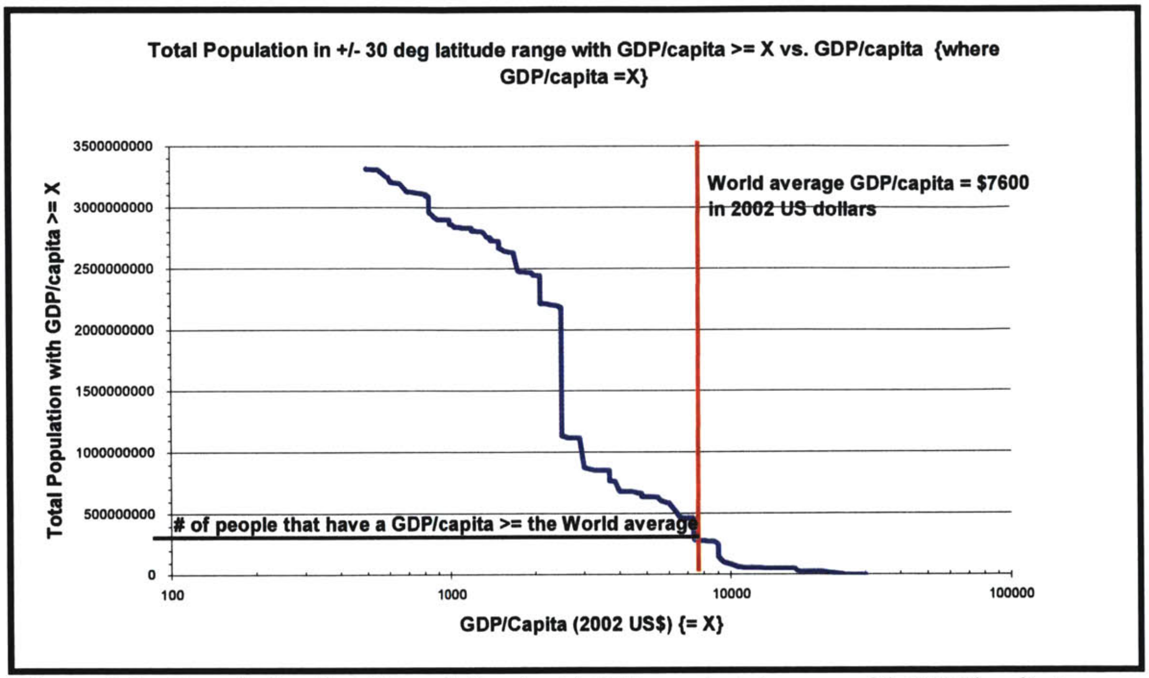


Figure 2-9: Cumulative Total Population in +/- 30° equatorial range with GDP/capita >= x, where x is the GDP/ capita

In summary, the data gleaned from the developing world database leaves the astute reader with two major conclusions. Firstly, a satellite system specifically developed to address the connectivity inequities of the developing world as proposed in this thesis is an immediate and extremely needed solution to a continuously exacerbating digital divide inequity. Secondly, there are non-trivial economic inequities which underscore the fact that developing world countries would be afforded enormous advantages through the introduction of a communications medium that is not dependent on the country's specific infrastructural maturity state and which is affordable and applicable to extremely marginalized communities. Hence the developing world has a yet untapped, immense potential to be a bustling market base for connectivity applications. With informed hindsight on the part of system designers to ensure the satellite system's applications are not technologically overly elaborate and provide the needed connectivity at minimum cost, this thesis's proposed system would make serious inroads in increasing access to many of the world's most basic social needs.

The current satellite system industry is technologically mature but yet to make impressive strides in the social good, policy and economic contexts. Satellite system design of the future must be revolutionized such that system designers endeavor to design for a multiobjective problem for which the objectives are:

- affordability for market bases most in need
- basic technical capability to carry out desired connectivity
- efficient design within current policy context
- adherence to the regulatory framework and,
- seamless incorporation (as is possible) within desired region/s of coverage's already existing mode/s of communication

Chapter 3

The Technical and Economic Feasibility of a Satellite Communication System for the Developing World

3.1 Introduction

Chapter 3 commences with a description of and rationale for the application that the proposed satellite system will deliver. The Chapter then sets up the analysis for the technical and economic feasibility of the proposed satellite communication system for the developing world. This feasibility analysis commences with a presentation of the details of the MATLAB based satellite communication simulation for the zonal equatorial coverage, proposed satellite system. The details of the SMS version of the simulation are presented along with a presentation of how the feasibility analysis was carried out. The results of the case study along with a discussion of the implications of the results are then discussed.

3.2 Delivering Innovative Mobility

3.2.1 An Assessment of the Intended Satellite Application

As a result of the affordability of the intended service being a major concern in the system design process for the proposed satellite system for the developing world, the development of extremely low-cost end user terminals with low cost-per-function connectivity costs must be a principal design objective. To this end, the envisioned goal of the proposed satellite system is to create a low cost non-realtime paging system for developing countries in the +/-30° latitude equatorial belt. The paging application would provide short messaging services (SMS) for its customers akin to the SMS service that is now quite popular amongst mobile phone users. SMS allows users to send a recipient a text based message using a given end user terminal. Currently the industry norm is that the fixed SMS message length is 160 characters but longer messages can be sent by being broken up into multiple messages. Because illiteracy amongst the poor is a major concern, the paging end user terminal could also be structured such that there would also be icons representing key messages such as "I have to cancel the plan we agreed on," or "I am at the desired location" or "The person or thing is not there" for example. The presence of such icons would extend the applicability and relevance of the application amongst marginalized communities.

The phenomenon of messaging has become an integral and very popular use of the portable Internet in today's mobile information society. The decision to have messaging be the application of choice for the system proposed by this thesis was driven in no small part by the fact that SMS has been proven to bring desired connectivity without discriminating costs. As evidence of this fact, the frequency with which text messages are sent around the world speaks for itself. China, which is a leading force in text messaging, sent a total of 220 billion text messages in 2003. [CD04] During the month of March in 2004 some 2.1 billion text messages were sent in the UK. [TEXT04] In the Philippines, despite its lackluster economic stance, as recently as 2002, Filipinos held the rank of first place in the world for SMS messages sent and received by each mobile user. At the height of the SMS boom, statistics showed that Filipino users sent an average of 20 text messages per day. [ITU04] Filipino operators have also initiated the use of SMS on fixed-line telephones. Consequently, within the realm of the portable Internet, the unprecedented success of text messaging has undoubtedly taken the industry by surprise. However for the reasons given in Section 2.3 and other parts of the discussion in this thesis thus far, the use of satellite systems in rural regions as yet untouched by any form of terrestrial-based wired or wireless connectivity medium is most certainly a needed service that has an undeniable role to play in attempts to bridge the digital divide.

With portable messaging end-user terminals becoming more resourceful and multi-modal, messaging has advanced from being an entertaining way to communicate - mainly utilized by the elite, to being an essential communication and business tool for person-to-person and private sector to customers interactions. Globally, SMS has become a revenue generating means to be reckoned with. It is being useds to inform, transact business within, organize, entertain and facilitate our increasingly busy lives. From business to governments to institutions to spouses and so many others, the high penetration of portable end user terminals and the cheap costs, coupled with the ubiquity of access and instantaneousness arrival times has resulted in messaging being used to promote goods, keep families in touch and various other applications which are greatly influencing the course of today's society.

3.2.2 Ingenious Messaging Applications

Airlines like Virgin Blue have introduced SMS check-in services where a barcode containing reservation details is sent to the end user terminal which is scanned at check-in. Mobile marketing campaigns are now quite common with different techniques such as competitions, SMS-based promotions, m-coupons, alerts etc. being used to link to targeted audiences. The traditional pink slip has also been digitized with SMS being used in countries like South Korea and the UK to inform employees of their redundancy. It is also becoming a means of court room evidence, playing a decisive role in many criminal investigations. [ITU04]

3.2.2.1 Saving Lives through Portable Messaging

Multimedia Messaging Service (MMS), wherein a photo can be sent as if it were a text message from a designated sender to a receiver, is being used by accident services in the UK to inform hospitals of the state of accident victims before they arrive at the Emergency Units. The service, operated by Orange UK and Fife Fire and Rescue Service, allows rescue workers at the scene of an accident to take photographs of casualities and immediately send photos by MMS to Dunfermline's Queen Margaret Hospital which also has mobile end user terminals and can thus receive the pictures in real time. Doctors then assess the magnitude of the injuries and organize the appropriate medical teams. Additionally, they can also determine whether they need to travel to the site of the accident or whether the victim's state can facilitate him or her being transported to hospital before treatment is administered. This is a more advanced application that has immense promise to improve the quality of health care in the critical first few moments following an accident. [ITU04]

Many more intriguing applications exist, in South Africa, SMS is being used to help HIV patients with the complicated process of taking drugs. The drugs each person has taken daily is recorded via an SMS message by the caretaker who travels through the village, this information is sent via text message back to the town hospital for recording in a database. This 'paper-less' method has greatly improved this aspect of HIV health care in South Africa. [BBC05] SMS is also being used in China and South Africa to allow people to vote and share their opinions on issues related to their Governance resulting in increased participation in the civic process, which should not be taken for granted given the recent history of China. In Kenya, SMS is used by rural farmers to find out the price for their produce in the main markets so they can ensure the "middle man" is presenting them with fair prices for their harvest. [ITU04]

On the more technical side of things, messaging being the application of choice lends numerous benefits. Firstly, affordability must be the driving tenet behind application choice and it satisfies this criterion. Secondly, the end user terminal is basic, that is, it is not an instrument that promises to 'do it all' but rather is focused on delivering a specific single task (i.e., messaging) well. There is not a significant memory storage requirement with these systems, though there is some memory required to store old messages. This further contributes to the end user terminal being small, compact and not technologically elaborate. The provision of the application of messaging means the system can operate in store and forward mode instead of real time which helps to significantly drive down costs. Additionally, the low power electronics involved has the capacity to enable extended operation using batteries or any available renewable energy source (such as solar powered terminals). This reduced power need in comparison to other communications facilitating terminals and in concert with simple antenna requirements, also helps to drive down costs.

In sum, the exciting applications for messaging mentioned earlier in concert with these technical benefits demonstrate that messaging is a proven popular communication medium which has confirmed that it can reliably deliver the desired connectivity at an affordable cost. Thus the proposed satellite system in this thesis attempts to capitalize on the immense potential of messaging services to deliver greater access to basic social services and in so doing empower the poor.

3.3 The Simulation Model for LEO Communication Systems

3.3.1 Purpose of Model

Many different fields comprise the background knowledge necessary to formulate a LEO satellite system. The system designer must be adept, inter alia, at spacecraft design, launch vehicle matching and pricing, orbital dynamics, recommendations for end user terminal design, satellite communication and cost analysis. In order to simulate an envisioned satellite system, a MATLAB based simulation was built by Chang and de Weck [deWDC03a] which based on the desired purpose of the satellite system can model the important elements of the satellite design constellation problem. In the process of the simulation, high level design decisions such as the constellation type or the minimum elevation of the satellites are mapped to system performance, lifecycle cost and capacity, where capacity is indicative of the number of simultaneous users. The simulation is focused on trading off lifecycle cost (LCC) with system capacity, while keeping the communication performance per channel constant.

For the particular instantiation of the simulation in this research, it is important to understand the functional system requirements of the system. In this case the fundamental requirement of the LEO constellation system is that it provide non real-time, store and forward based, good quality messaging communication. Depending on certain engineering fundamentals such as the multiple access scheme and diversity of the system, technical specifications required to meet the customer's demands for the messaging system in the form of bit error rate, data rate per user channel and link margin are derived. These three metrics form the requirement vector **r**.

Another important consideration is the design vector **x** of the system that the system designers have flexibility to change at the early stage of the design process. For this system there are nine design variables which are expounded upon further in this Chapter. It is the exhaustive combination of all possible design variable values that form the design space. While each architecture in the design space has a specific design vector **x**, they all share a vector of constants **c**. Because each architecture shares the same sub-technology, the values of the constants are the same for each of these architectures. For example, each architecture utilizes the same modulation scheme and the Nyquist filter rolloff factor is the same for each system.

Of equal importance as design variables and system constants are the important policy constraints **p** stipulated by governing organizations such as the FCC or the ITU. As Larson and Wertz inform us, regulatory constraints exist on the choice of frequency band, transmission bandwidth and power flux density. For example, international agreements have set frequency bands for space communications. These agreements were established by the ITU and the World Administrative Radio Conference (WARC). They are administered in the US by the FCC for commercial users and the Interdepartmental Radio Advisory Committee for military users. [WLJR99] The policy constraints, **p**, design requirements, **r**, and system constants, **c**, are shared by all architectures across the design space and together form the known metrics of the system.

Based on the known metrics, it is the task of the system designer to construct a means to connect from the design space to objective space in order to fully understand and probe the trade space of the system. This will facilitate prediction of the system performance once the metrics **p, r** and **c** are known and a set of design vectors **x** is provided. In order to provide reliable and real time prediction of system performance capability, the computer based model referred to previously was developed to mimic real world designs in a computer environment. The simulation facilitates the following mapping from design space to objective space: **J** = f(**x**,**c**,**p**,**r**), where J is the objective vector. It is important that the fidelity of the model be ratified. In order to accomplish this ratification, a vector of benchmarking metrics **B** is also generated by the simulation to see how it matches up with real systems. The system designer can be confident that the simulation model is reproducing reality if the comparison matches up with real systems favorably.

3.3.2 Limiting Assumptions of the System Model

The model is solely designed to simulate LEO constellation systems, as such there are some inherent limiting assumptions that pertain to the system. These are as follows:

- All orbits are circular.

- The satellite system simulation is designed to provide coverage to the 30° latitude north to 30° latitude south equatorial range.

- The system has a diversity of one.

- LEO systems are situated between the altitudes of 500 and 1500 km. The launch vehicles modeled by the simulation can launch satellites to an altitude of 2000km. The system thus assumes that all systems will only need to be launched to an altitude of 2000km.

- The average elevation angle for LEO systems is under 30°. The simulation will successfully model systems with elevation angles in the range of 0° to 40°.

- In the event that the satellite mass is extremely large, the simulation will return no solution. However since launch vehicles such as Ariane 5 can lift six tons of payload to the geostationary transfer orbit, it is hard to imagine any design that would be unable to find a launch vehicle capable of lifting it to the much lower LEO orbits.

- The only multiple access schemes modeled are multiple frequency-time division multiple access (MF-TDMA) and multiple frequency-code division multiple access (MF-CDMA). The multiple access scheme employed informs the method by which multiple channels are connected with a single satellite. MF-TDMA and MF-CDMA are the two most popular multiple access schemes in use in LEO systems today.

While these limitations are in line with LEO systems, future system designers should keep them in mind to ensure technically sound results are outputted from the model.

3.3.3 System Architecture Evaluation Framework

We are now ready to build, implement and use the system model. The following six steps proposed by de Weck and Chang carry out the entire system architecture evaluation framework process. The first four steps build and implement the modules while the last two steps demonstrate how the model is used in this analysis.

1. Choose the elements and bounds of the architectural design space inputs which include the design vector **x**, constant vector **c**, policy vector **p**, and requirement vector **r**; and outputs that include the objective vector **J**, and benchmarking vector **B**.

2. Build the mapping matrix between inputs and outputs and subdivide the problem into modules which match the system's physical and functional characters. Define clear cut interfaces between modules.

3. Implement and integrate the modules based on technological, physical, economic and policy relationships such as constellation geometry, astrophysics, communication theory, cost estimating relationships and market estimation. Implement the individual modules

and test them in isolation from each other. Then integrate the modules into an overall simulation.

4. Benchmark the simulation against the data of reference systems. Tune and refine the simulation as necessary (Loop A in Figure 3-1).

5. Conduct a systematic trade space exploration using a full factorial run that covers the entire possible range of design variables.

6. Identify and post-process the Pareto optimal set. If no acceptable Pareto optimal solution is found, the design space needs to be modified (Loop B in Figure 3-1). Once the Pareto optimal solutions are arrived at, extract a subset of Pareto optimal architectures that are non-dominated for further study.

Figure 3-1 shows a block diagram of the proposed architectural design space exploration methodology modified to suit the research proposed by this thesis.

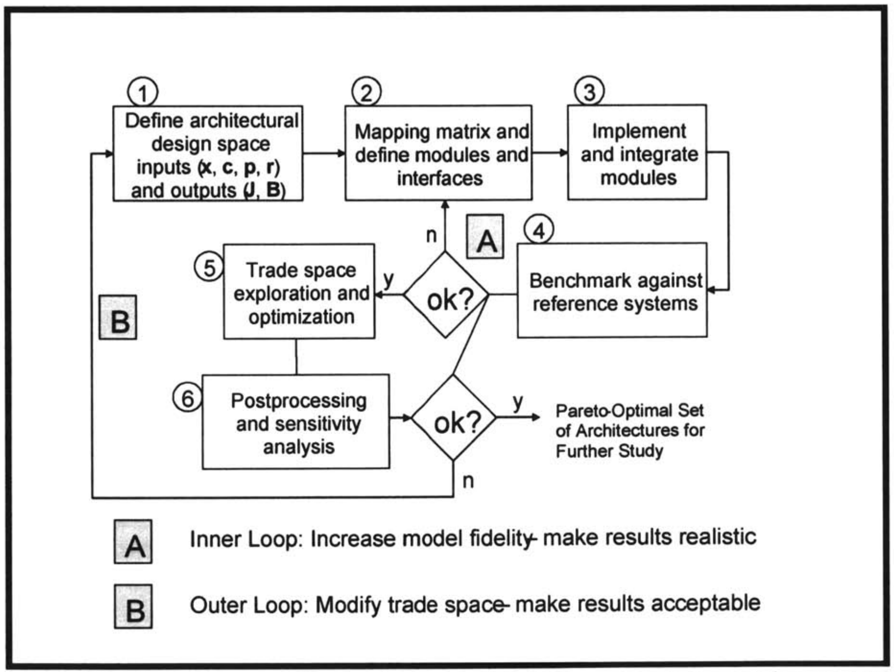


Figure 3-1: Architectural trade space exploration methodology [deWDC03a]

3.3.4 Implementing and Testing the System Model

The proposed system architecture evaluation framework of Section 3.3.3 is applicable to many classes of complex systems but in this research it will be used to explore the trade space of zonal equatorial LEO systems. In this section the first four steps of the previously mentioned system architecture evaluation framework will be explored. We begin by clearly defining the input and output vectors of the simulation, and end with benchmarking the simulation against an actual messaging system that has been launched in the recent past called Orbcomm. Orbcomm is a global messaging LEO system that started to provide full service in 1998. In addition to global two-way data (wireless email, fax etc.) and messaging applications, it also provides tracking and monitoring capabilities for high level industries such as the U.S. Armed Forces, transportation, marine, aviation, automotive, utility, oil, and gas industries [ORBM].

3.3.4.1 Input (Design, Constants, Policy, and Requirement) Vectors and Output (Objective and Benchmarking) Vectors Definition (Step 1).

Figure 3-2 shows the vector of design variables **x**, constants **c**, policy constraints **p**, performance requirements **r**, objectives **J** and benchmarking vector **B** that are utilized in and produced by the system model. The Figure also illustrates which of the vectors are inputs into the model and which are outputs.

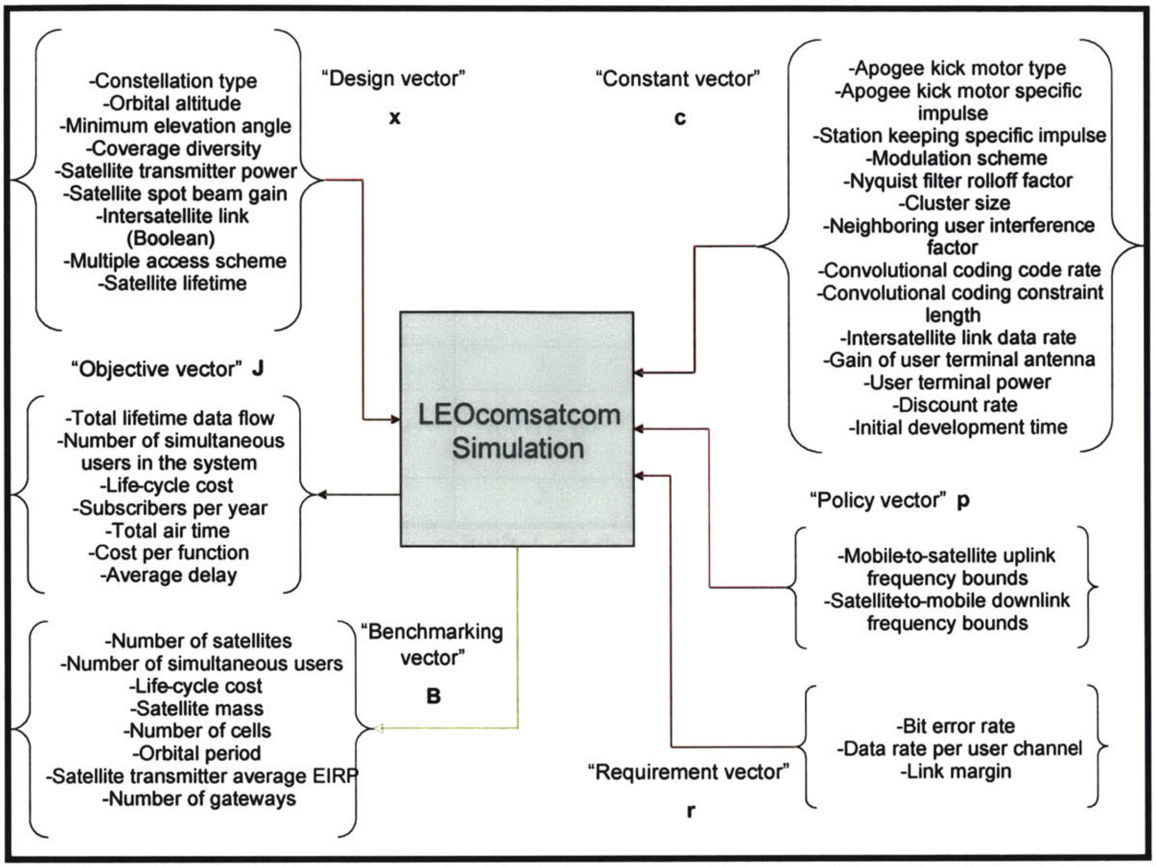


Figure 3-2: Input-output mapping of LEO communication satellite constellation simulation [deWDC03a]

The design vector **x** is instrumental in framing each architecture as it captures the architectural design decisions and is the sole input into the system that the system designer can change for each architecture to test the effect on system performance. For this SMS based instantiation of the simulation, the design vector was subject to the bounds or discrete values shown in Table 3.1.

Symbol	Variable	x_{LB}	x_{UB}	Unit
C	Constellation type	Walker	Walker	[-]
H	Altitude	500	1350	[km]
ε_{min}	min elevation	5	35	[deg]
Div	Diversity	1	1	[-]
P_t	sat transmit pwr	5	200	[W]
$G_{t\,dB}$	sat antenna edge cell spot beam gain	2	2	[dBi]
ISL	inter sat links	1	0	[-]
MAS	Multiple access scheme	MF-TDMA	MF-CDMA	[-]
T_{sat}	sat lifetime	5	15	[years]

Table 3.1: Design variable definition, **x** [deWDC03a]

The constant vector, **c**, illustrated in Table 3.2, includes technical parameters that are assumed fixed throughout the design space exploration process. These technical parameters are assumed fixed either because they are determined by existing technologies, or because their variation will still result in technologically sound solutions. But nevertheless, these parameters are use to compute some important calculations during the simulation.

Symbol	Constant	Value	Unit
AKM	apogee kick motor type	2 (3-axis-stablized)	[-]
$AKMI_{sp}$	apogee kick motor specific impulse	290	[s]
$StationI_{sp}$	Station keeping specific impulse	230	[s]
MS	modulation scheme	QPSK	[-]
ROF	Nyquist filter rolloff factor	0.5	[-]
CS	Cluster size	1	[-]
$NUIF$	neighboring user interference factor	1.36	[-]
R_c	convolutional coding code rate	½	[-]
K	convolutional coding constraint length	9	[-]
R_{ISL}	intersatellite link data rate	0	[MB/s]
$G_{e\,dB}$	gain of user terminal antenna	0.7	[dBi]
P_e	user terminal power	0.5	[W]
D	discount rate	15	[%]
IDT	initial development time	5	[years]
$NGPCRF$	Non-government project cost reduction factor	0.8	[-]

Table 3.2: Constants definition, **c** [deWDC03a]

The policy vector, **p,** contains only the bounds of the frequency bands assigned by FCC. These values are based on the values declared by the Orbcomm system in their FCC filing. The policy vector **p**, is where other policy decisions, such as restrictions on the placement of gateways or the use of foreign launch vehicles could be included. The simulation includes a Boolean variable representing whether to use foreign launch vehicles or not. However it is usually turned off unless we want to test the effect of banning non U.S. launch vehicles.

Policy constraints	Orbcomm
uplink frequency bandwidth upper bound [MHz]	150.05
uplink frequency bandwidth lower bound [MHz]	148.00
downlink frequency bandwidth upper bound [MHz]	138.00
downlink frequency bandwidth lower bound [MHz]	137.00

Table 3.3: Policy constraints, **p** [deWDC03a]

For this research, the requirement for LEO communication satellite constellations is to provide satisfactory messaging communication. In order to provide the minimum acceptable messaging quality, the requirements **r** that include bit error rate (BER), data rate per user channel (R_{user}) and link margin (Margin) must be decided upon. The requirement vector **r** is dependent upon the following two design variables: the multiple access scheme (MAS) and the diversity (div). With the MAS taking values of MF-TDMA or MF-CDMA and the diversity being 1 throughout the analysis, the following requirements vector is obtained as shown in Table 3.4. It should be noted that the link margin value indicated is the margin for the satellite to end user terminal downlink. Also the data rate value shown is the equivalent subscriber unit downlink data rate. The BER , R_{user} , and Margin values were all influenced by publicly available data on the Orbcomm system.

Design variables		**Requirements**		
Multiple access scheme	Diversity	Bit error rate (*BER*) [-]	Data rate per user channel (R_{user}) [kbps]	Link margin (*Margin*) [dB]
MF-TDMA	1	1e-6	4.8	4.4
MF-CDMA	1	1e-5	2.4	3.3

Table 3.4: Requirements definition, **r** [deWDC03a]

The objective vector J captures all the metrics by which the "suitability" of a particular architecture can be evaluated. As Table 3.5 demonstrates, the objective vector shares insight as to the total lifetime data flow that represents the total communication traffic (throughput) throughout the lifetime of the system, the number of simultaneous users the system can support (i.e., its capacity), the life-cycle cost, and the cost per function (CPF). Cost per function here is defined as the life-cycle cost divided by the total lifetime data flow. Note that all costs mentioned in this analysis are in 2002 United States dollars.

Symbol	Objectives	Unit
$R_{lifetime}$	total lifetime data flow (integrated)	[GB]
N_{users}	number of simultaneous users	[-]
LCC	life-cycle cost	[B$]
CPF	cost per function	[$/GB]

Table 3.5: Objectives definition, **J** [deWDC03a]

To prove that the simulation is producing trustworthy data, the results must be benchmarked against similar existing satellite systems. In that regard the simulation also outputs a benchmark vector which is comprised of technical specifications that result from the design process. If the simulation uses the same design vector, **x**, as an existing satellite system, then a comparison between the benchmarking vector of the simulation and the existing operational system should not show a major variation in resulting technical specifications. A high fidelity simulation will have technical specifications that are very close to that of the real system from which its design vector was modeled. Table 3.6 shows the technical specifications contained in the simulation's benchmarking vector, **B**. Some of these variables are also contained in the objective vector, **J**.

Symbol	Benchmarking variables	Unit
N_{sat}	number of satellites	[-]
N_{users}	number of simultaneous users per satellite	[-]
LCC	life-cycle cost	[B$]
M_{sat}	satellite mass	[kg]
N_{cell}	number of cells	[-]
T_{orbit}	orbital period	[min]
$EIRP$	sat xmit average EIRP	[dB]
$N_{gateway}$	number of gateways	[-]

Table 3.6: Benchmarking vector, **B**, definition [deWDC03a]

3.3.4.2 Define, Implement and Integrate the Modules (Steps 2 and 3)

Step 1 of the System Architecture Evaluation Framework process, i.e. the definition of the input and output vectors of the architectural trade space has now been completed given the discussion in section 3.3.4.1. We will now enter the inner loop A of Figure 3-1 in which the simulation modules are defined, implemented, integrated and benchmarked. It is within this important loop that any necessary changes to the simulation required to have it align with its intended function and reflect reality are implemented. This is of the utmost importance to ensure the simulation's results will benchmark favorably with existing systems. In this discussion, the state of the completed model at the end of the iteration process is presented.

The main focus of this section is steps 2 and 3 of the evaluation framework which are to define, implement and integrate the system's modules. In order to ensure the simulation benchmarks well, great effort was undergone to ensure the economic and physical laws that underlie the system are accurately defined and reproducible. The following discussion gives an overview of the overall structure of the simulation then takes it one level down to a description of each module of the simulation in conjunction with a description of the module's implementation.

3.3.4.2.1 Simulator's Overall Structure

The satellite system simulation structure is based on a modular framework. Speaking generally the simulation's modules can be broken up between technology and economic domains, each module falling squarely into one category or into the other. A major concern of the simulation developers was that they wanted to ensure that if a single module needed to be changed that this would not necessitate changes in other modules of the system. In such a large scale simulation this goal is imperative and was accomplished by having the modules communicate with each other through input-output interfaces. Consequently, as long as the interface was not perturbed, a change in one module of the simulation would not cause for attendant changes in other modules of the system. The physical or functional relationship between the components of the simulated satellite system is enacted through the communication that takes place between the modules. The complete model structure is shown in Figure 3-2 wherein each box represents an individual MATLAB file within the simulation. Note that the Market module shown is not utilized within the simulation.

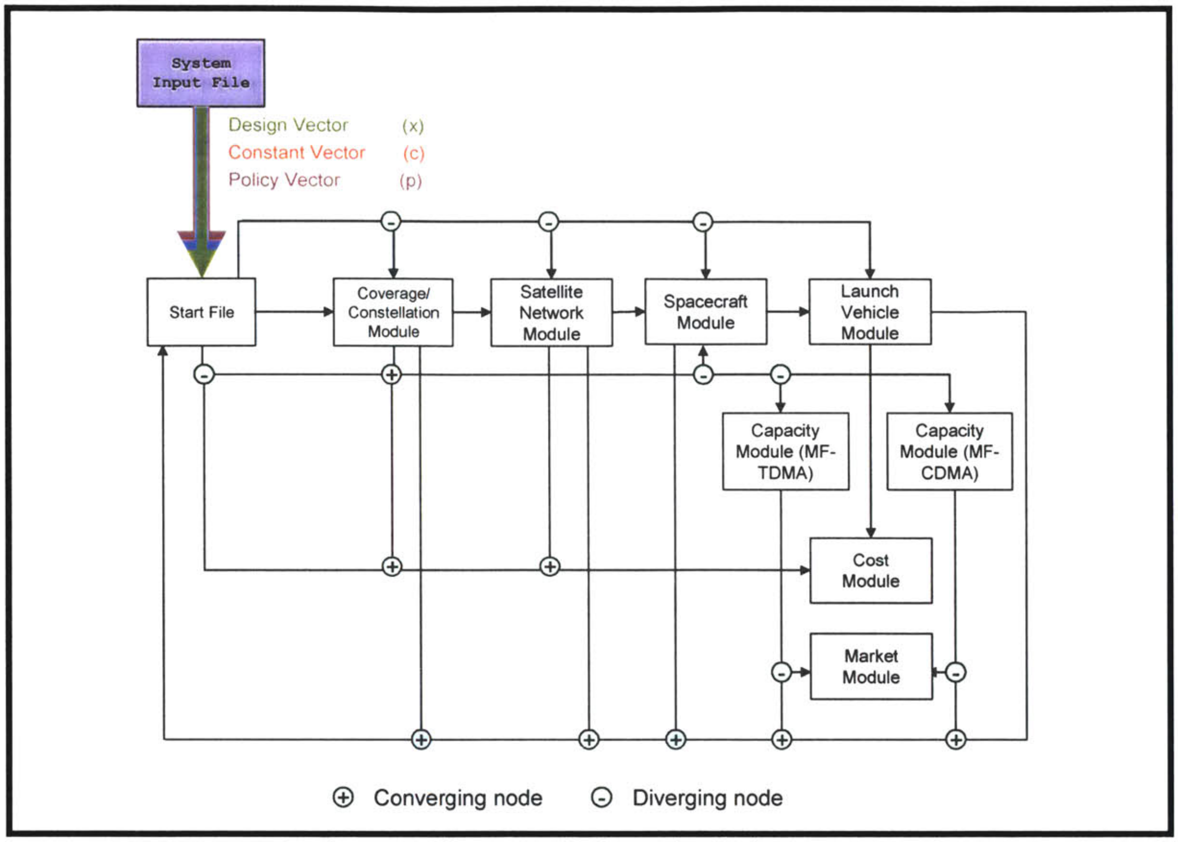


Figure 3-3: Communications satellite constellation - simulation structure. [deWDC03a]

The simulation model gets kicked off by the System Input File (SIF). The SIF entails all the values of the design vector **x**, constant vector **c**, and policy vector **p** as inputted by the satellite system architect. The SIF then communicates the values of these vectors to the Start File (SF). Start File then produces the requirement vector **r,** influenced by the design vector fed in by the SIF. The Start file is an integral part of the system model as this is the main warehouse for the summoning and execution of each module in the simulation in a specific order. The input-output interfaces that facilitate communication between the modules also exist within the SF. The modules along with their main roles are as follows [DC04]

1. Coverage/Constellation Module (CCM) that defines the constellation structure and coverage geometry

2. Satellite network module (SNM) that determines the network topology

3. Spacecraft module (SM) that computes the physical attributes of the spacecraft

4. Launch vehicle module (LVM) that selects the capable and most economical launch vehicle

5. Capacity modules (CM) that compute the satellite capacity of different multiple access schemes

6. Total cost module (TCM) that computes the life-cycle cost of the system and also computes the cost of the messaging end user terminal

7. The results from the Market module (MM) are superseded by the analysis in section 3.5 which details the post processing of the Pareto optimal solutions.

The SF calls and runs all the modules of the system. The results of the simulation are subsequently stored in the objective vector **J** and the benchmark vector **B** to facilitate post-processing and analysis by the system designer. An in-depth description of the modules has been prepared by de Weck and Chang and is included in Appendix B.

The discussion in Appendix B also includes a detailed description of the changes made to the simulator to facilitate this study's requirement for adequate messaging capability. Nonetheless, as a brief summary, the changes made to the simulation for the purpose of this research are that firstly, the design, requirements, policy and constants vectors were all changed to suit the needs of this messaging based system. Secondly, the coverage constellation module was changed so that it employs a numerical optimization of Walker constellation designs developed by Lang and Adams [TLWA97] specifically catered to the +/- 30° equatorial belt. As such, the constellation structure and coverage geometry are defined specifically for the region of interest. Thirdly, an end user terminal module was defined which determines the cost of the end user unit given certain end user terminal design requirements that the system operator is given the flexibility to decide upon.

A fourth change is that the number of staff members accounted for in the cost module was reduced by half in keeping with the reduced system coverage requirement which reduces the need for as many staff members. The fifth change was that within the satellite network module, the outputted number of gateways parameter's calculation no longer incorporates values based on Globalstar's parameters, but on Orbcomm's. Finally, the launch module was changed to account for the fact that the ranges within which launch vehicles would apply needed to be in line with the structure of the messaging system.

3.3.4.3 Benchmark against Reference Systems (Step 4)

de Weck and Chang performed benchmark tests of the simulation to test its fidelity. [deWDC03a] The simulation was run using the input parameters identical to those of four real-world systems: Iridium, Globalstar, Orbcomm and SkyBridge. Iridium, Globalstar and Orbcomm have all previously been mentioned. SkyBridge is a proposed large scale, pioneering, LEO broadband multimedia satellite system. For each of the four systems, the design variables, constants, policy constraints and requirements vectors were collated and each independently run through the simulator to see how its benchmarking vector and objective vector matched up with the known attributes of the four real-life systems.

The benchmarking results were that for the chief system attributes of number of satellites, satellite mass, system capacity, and lifecycle cost, the discrepancies between the real-life/planned systems and simulated systems were on average less than 20%. The fidelity of the simulation acceptably satisfies the research needs of the system studies that the simulation was envisioned to assist. Table 3.7 illustrates the benchmarking results for the SMS instantiation of the simulation (second column of Table 3.7) compared to the results the simulation produced for the Orbcomm system under the work by de Weck and Chang (third column of Table 3.7) and how these both compare to the actual parameters of the real-life Orbcomm System (fourth column of Table 3.7). The input design variables into the simulation to conduct the benchmarking of the proposed SMS based system were made to match those of Orbcomm.

Benchmarking vector, **B**, variables	Simulation of proposed SMS-based system	Simulation of Orbcomm	Actual Orbcomm
number of satellites	19	39	36
number of simultaneous users per satellite	219	216	N/A (store & forward)
life-cycle cost [billion $]	0.66	1.79	0.5+
satellite mass [kg]	45.34	45.34	41.7
number of cells	1	1	1
orbital period [min]	101.0	101.3	N/A
sat xmit average EIRP [dBW]	18	18	10.7
number of gateways	5	64	9

Table 3.7: Benchmarking results of the proposed SMS-based system and the simulated Orbcomm system against the actual Orbcomm system

Note that the difference in the benchmarked number of satellites in the proposed SMS system and the simulated Orbcomm system as shown in Table 3.7 is due to the fact that the simulated SMS-based system only serves the +/-30° latitudinal equatorial belt (hence the reduction in number of satellites). The LCC of the proposed SMS system is also different from the simulated Orbcomm system due to reduced costs stemming from a minimized number of satellites requirement, staffing needs which are commensurate with the scale of the system and other such cost reducing factors. The number of gateways parameter is also different due to reduced coverage needs. As of this point we have completed the inner loop A shown in Figure 3-1, the next step is to explore the trade space of the proposed SMS-based LEO communication satellite system using the simulation model. Given these differences in input the benchmarking process provides reasonable results.

3.4 Trade Space Exploration and Optimization (Step 5)

At this stage, we will run a full factorial exploration of all exhaustive combinations of selected values of the design variables. This allows the system designer to get a good understanding of the trade space which is integral to an informed system design process. The discrete value or choice of values for each design variable used in the full factorial run is illustrated in Table 3.8. The result of the design space exploration process will show the extent of designs or objective values that can be arrived at through the simulation. The next step will be to filter out the set of non-dominated architectures that define the Pareto front of the design space. The Pareto optimal architectures resulting from the simulation are distributed along the Pareto front.

I	Variable	Values	Unit
1	constellation type	Walker	[-]
2	Altitude	500, 825, 1350	[km]
3	min elevation	5,20,35	[deg]
4	Diversity	1	[-]
5	sat xmit pwr	5,200	[W]
6	sat antenna edge cell spot beam gain	2	[dBi]
7	Inter sat links	0, 1	[-]
8	multiple access scheme	MF-TDMA, MF-CDMA	[-]
9	satellite lifetime	5, 10, 15	[years]

Table 3.8: Design variable values for the full-factorial run

The full factorial run computed in this simulation ran a total of 216 designs. The results are shown in the full factorial curve in Figure 3-4. Each point on the plot in Figure 3-4 represents an individual architecture which has its own distinct objective vector, **J**, and design variable **x**. The y-axis represents the LCC in billions of 2002 US dollars while the x-axis represents the system capacity in terms of the number of simultaneous users that the system can support.

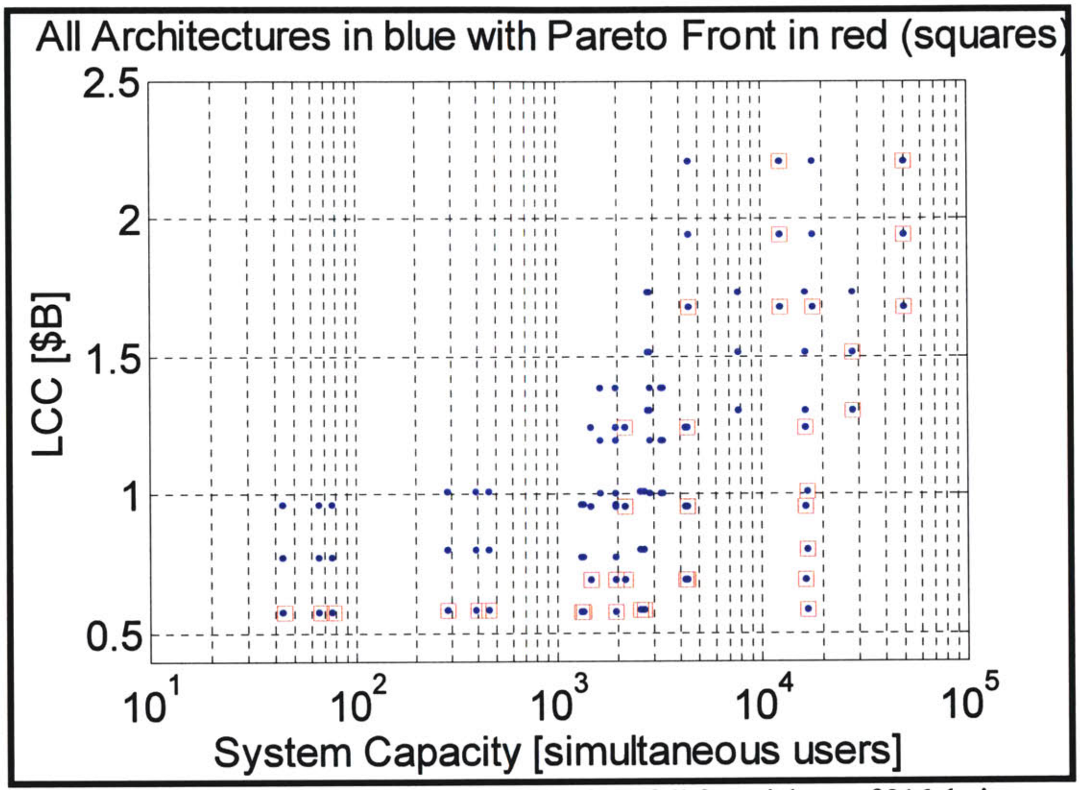


Figure 3-4: LCC vs. System Capacity plot for a full factorial run of 216 designs

One of the first trends that this full factorial plot shows is that in general systems with larger capacities have higher costs and vice versa. This trend does not come as a surprise as all other things being equal it takes greater capital to simultaneously serve a greater number of customers. Now given the full factorial results how does one begin to make sense of all the system architectures shown in this plot? If the objective vector **J** of a satellite design is non-dominated in comparison to the objective vectors of all other designs in the design space, then this design is Pareto optimal and is of interest to the system designer. Note that there are some designs in Figure 3-4 that appear to be dominated despite the use of a strong Pareto filter. Further work should be conducted on this trade space to rid it of these dominated points which are appearing as Pareto optimal. This is recommended for future work in the Future Work Section of Chapter 5.

3.4.1 Non-dominated (Pareto) Architectures

What does one specifically mean when a non-dominated or Pareto optimal solution has been identified? The following analysis adapted from de Weck answers this question. [deW03] Let $\mathbf{J}^1$ and $\mathbf{J}^2$ be two different objective vectors in the same objective space S. In the case of maximization, $\mathbf{J}^1$ dominates $\mathbf{J}^2$ if and only if (iff):

$$J_i^1 \geq J_i^2 \ \forall\, i \quad \text{and} \quad J_i^1 > J_i^2 \text{ for at least one } i \tag{3.1}$$

A design $\mathbf{x}^* \in$ S is Pareto optimal iff its objective vector $\mathbf{J}(\mathbf{x}^*)$ is non-dominated by the objective vectors of all the other designs in S. In other words, in optimization literature, design $\mathbf{x}^*$ is 'non-dominated' if it is impossible to move feasibly from it to increase an objective without decreasing at least one of the other objectives. Note that $\mathbf{x}^*$ only approximates a Pareto optimal solution, due to the way in which the design problem has been transformed into a combinatorial problem. But for the purpose of finding near-Pareto optimal solutions in the design space of this research, this difference can be ignored.

The front formed by the Pareto optimal solutions in the design space is called the Pareto front. In Figure 3-4, the Pareto front is plotted along the lower left to the lower right boundary of the design space. Among the 216 total designs, 16 designs are valid Pareto optimal points (7.4%). Understanding these particular Pareto optimal solutions shares great insight into the nature of the trade space of the system. A key insight is that studying these designs allows the system designer to understand which design variable values lead to desired objective values and which do not. The design exploration process can be understood as a "filter", which serves to find the small subset of efficient solutions. The values for the Pareto front architectures' total capacities, life-cycle costs, and cost per year to the end user to send and receive messages are listed in Table 3.9. The Pareto front architectures' design variables are listed in Table 3.10. Both tables are ordered from systems with the lowest to the highest life-cycle costs.

Design	Capacity	LCC	Cost/Year
Number	(persons)	(B US$)	($/year)
1.00	77.00	0.58	221.68
2.00	1,375.00	0.58	12.41
3.00	66.00	0.58	258.62
4.00	1,331.00	0.58	12.82
5.00	44.00	0.58	387.94
6.00	1,958.00	0.58	8.72
7.00	2,679.00	0.58	6.45
8.00	16,720.00	0.58	1.03
9.00	2,603.00	0.58	6.64
10.00	16,720.00	0.79	0.70
11.00	16,720.00	1.01	0.59
12.00	27,930.00	1.30	1.38
13.00	27,930.00	1.51	0.80
14.00	49,830.00	1.68	1.00
15.00	49,830.00	1.94	0.58
16.00	49,830.00	2.20	0.44

Table 3.9: System Total Capacity, LCC, and the Cost per Year to send and receive messages for the Pareto Optimal Designs

Design	Altitude	Elev	T. Power	MAS	Sat Lifetime
Number	(km)	(deg)	(W)	TDMA/CDMA	(years)
1.00	1,350.00	5.00	5.00	1.00	5.00
2.00	1,350.00	5.00	5.00	2.00	5.00
3.00	1,350.00	20.00	5.00	1.00	5.00
4.00	1,350.00	20.00	5.00	2.00	5.00
5.00	1,350.00	35.00	5.00	1.00	5.00
6.00	1,350.00	35.00	5.00	2.00	5.00
7.00	825.00	5.00	5.00	2.00	5.00
8.00	825.00	20.00	5.00	2.00	5.00
9.00	825.00	35.00	5.00	2.00	5.00
10.00	825.00	20.00	5.00	2.00	10.00
11.00	825.00	20.00	5.00	2.00	15.00
12.00	825.00	20.00	200.00	2.00	5.00
13.00	825.00	20.00	200.00	2.00	10.00
14.00	500.00	20.00	200.00	1.00	5.00
15.00	500.00	20.00	200.00	1.00	10.00
16.00	500.00	20.00	200.00	1.00	15.00

Table 3.10: Design Variables of the Pareto Optimal Designs

Observation of Tables 3.9 and 3.10 will illustrate a few noteworthy generalizations about the Pareto optimal designs of LEO satellite constellations for messaging communication services to a zonal equatorial region. The first point to note is that by design, all architectures produced by the full factorial trade space exploration process were Walker constellations with a diversity of 1 and a satellite antenna edge cell spot beam gain of 2dBi. In general, systems with lower life-cycle costs were stationed at high altitudes, had low satellite transmitter power values, and had elevation angles that varied between high and low values.

The Pareto optimal satellite systems produced became expensive at low altitudes, higher elevation angles and high transmitter power. The highest cost systems employed the MF-TDMA multiple access scheme and had a high system lifetime. At the most expensive levels such systems catered to a capacity of 49,830 simultaneous users but at an LCC of $2.2 billion US dollars. On the other hand, the least expensive systems had high altitudes, a mixture of high and low elevation angles, low transmitter power, varied between MF-TDMA and MF-CDMA and had low system lifetimes. The most efficient low cost system had a capacity of 16,720 simultaneous users which is approximately 34% of the capacity of the high cost systems, but did so at approximately 26% of the cost with an LCC of $0.58 billion US dollars.

All optimal solutions did not have inter satellite links (ISL) and systems with significant cost and capacity benefits had short system lifetimes. These trends are in accordance with real world observations. The function of inter satellite links is to reduce the satellite system's requirements on the ground. Their implementation can realize real reductions in the number of ground stations needed, but this does not help to increase capacity (which is a goal of the optimization process). Furthermore, the development costs and additional weight requirements inter satellite links necessitate increases the system life-cycle cost. If it is believed that there could be policy and regulatory issues limiting the placement of ground stations in 'sensitive' locations then ISLs become a very wise choice. To this point, Chang reminds us in his work that the concept of ISLs was first developed for spy satellites by Motorola. [DC04] However the suite of requirements that become necessary upon the implementation of ISL does not render such systems Pareto optimal for this analysis.

The short lifetime design variable in the optimal designs is also not a surprise as longer system lifetimes mean more fuel is needed to keep the satellites in orbit. Further, a larger fuel requirement signals a greater satellite wet weight and more demanding launch capability requirements which serves to drive system costs upward. Admittedly, a longer system lifetime has the advantage of averaging the initial deployment costs over the system lifetime. Nonetheless, by and large for the developing world market, with affordability being the driving objective, low cost systems are most desirable. This affordability requirement lends to lower system lifetimes. Thus, the overriding attractive architectures from the Pareto front are those which orbit at high altitude, supporting relatively small amounts of users at low cost.

The astute reader could then ask whether amongst the Pareto optimal designs there exists a "most optimal" or "best" solution. The preferred solution depends on the goals of the system designer. Technically, by definition, all designs along the defined Pareto front are equally optimal. It is the overarching purpose envisioned for the system which will influence the system designer to choose a particular architecture along the Pareto front to be more "ideal" than another. For the purposes of this analysis it is desired to choose a Pareto point that is most likely to be agreeable with the economic constraints of its potential customers in the developing world, since affordability is a driving factor in this analysis. Thus a cluster of designs in the lower left half of Figure 3-4 will be chosen to see whether any could be a feasible architecture, affordable to those in the +/- 30° equatorial band. This analysis is conducted in the Post Processing of Section 3.5.

Table 3.9 details the values for the following objective variables: the total system capacity, the LCC, the cost per year to the user to send and receive a nominal amount of messages per year, (this nominal amount is 10 messages per user per day; the rationale for this choice is given in Section 3.5). If the system designer has a desired objective vector in mind for which he would like to find the matching design that results in this objective then he should use the design of the closest architecture to his desired objective in the trade space. Once the closest matching architecture is found then the system designer can make the mapping from objective vector space to design vector space. If there happens to be no architectural designs with objective values close to the desired objective then a full-factorial run with more values for each design variable could be performed to allow for a finer design space resolution. Now that the Pareto optimal solutions have been identified and detailed, step 4 of the architectural design space exploration process is completed. The next step is to conduct important post-processing of the Pareto optimal architectures.

3.5 Post Processing of the Pareto Optimal Solution (Step 6)

The goal of post processing is to extract the subset of Pareto optimal architectures for further study that are non-dominated and which harbor favorable characteristics given the system designer's goals. Once the 'ideal' architecture is filtered out, the nature of the optimal solution x* that produces this 'ideal' candidate architecture can be deduced. Knowledge of the optimal design vector shares keen insight as the system designer has control over the values within the design vector and thus knowledge of the values these design variables should take to produce the desired objective values greatly aids the system design process.

Figure 3-5 shows the cumulative number of users in the developing world region against amounts in US dollars that represent the percentages of GDP per capita that research has shown people are willing to spend on communication services. Harry E. Cook in his economic work [HC97] explains that irrespective of a person's income, the fraction of personal income that one would be prepared to spend on life's basic necessities is approximately the same across income levels. For instance, irrespective of level of income people tend to spend approximately the same fraction of their income on housing, food, services and other basic necessities. Through extensive economic research Cook has ascertained that people spend approximately 5% of their income on apparel and services. I hence surmised that approximately 3% of a person's income would be focused on services, a reasonable fraction of which would be spent on communication purposes, as while not having given specific numbers, it is documented that people in the developing world spend a greater fraction of their income on communication services than their counterparts in the developed world. [ECON05b]

With knowledge in hand of the dollar amount people are able to spend on communication services, data was then ascertained that indicated the cumulative population within the demarcated region that would be able to afford a communication service priced within this given 3% of income range. The red negatively sloping curve of Figure 3-5 is the result of curve fitting which represents the cumulative population within the developing world region against the fraction of GDP per capita spent on communication services. Thus if an observer were to choose any x axis 'GDP per capita spent on communication' point, they would be able to map the number of people within the developing world that would be able to afford a communication service priced at this amount. This is the exponential fit to an analysis similar to Figure 2-9 which plots cumulative total population in +/- 30° equatorial range with GDP/capita >= x, where x is the GDP/capita of the countries within the given range. The difference is that for the data in this fit, x represents GDP per capita spent on communications. The equation for this resulting exponential fit of the data is

$$f(x) = 4{,}148{,}704{,}450e^{-0.01158x} \tag{3.2}$$

This fit has coefficients with 95% confidence bounds. Let a = 4.149e+009 and let b = -0.01158 which are the two coefficients from equation 3.2 above. Within the confidence bounds 'a' can vary between 4.005e+009 and 4.293e+009 and similarly 'b' can vary between -0.01229 and -0.01086. R square is a statistic that measures how successful a fit is in explaining the variation of the data. The R square statistic was computed for this analysis and is 0.9622 for this fit. It should be noted that R-square can take on any value between 0 and 1, with a value closer to 1 indicating a better fit. For example, the R2 value of 0.9622 in this case means that the fit explains 96.22% of the total variation in the data about the average.

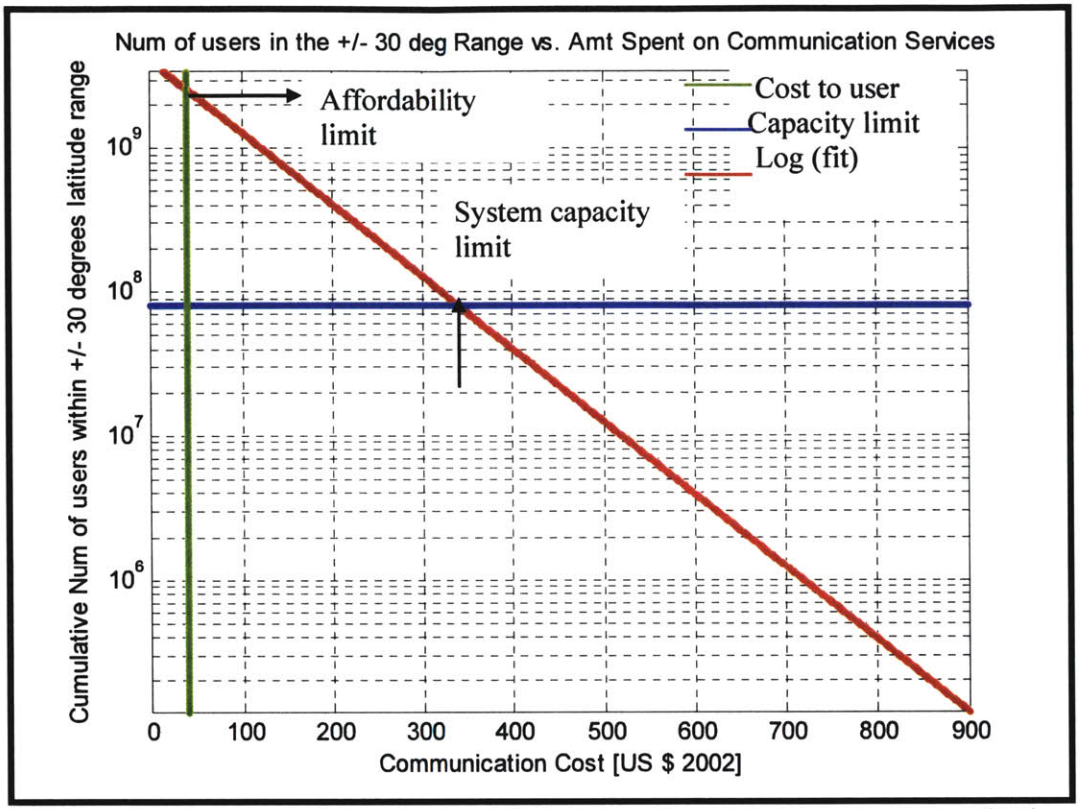


Figure 3-5: Number of users in the +/-30° range vs. amount spent on communication services

The x axis amounts in Figure 3-5 represent the cost per year for sending and receiving text messages plus the cost of the paging end user terminal and a standard one time activation fee. Note that an amortization schedule for the end user terminal has not been built in, but due consideration should be given to this issue in future work.

The cost of the end user terminal is an important variable. To ensure an informed analysis of what the price of the end user terminal should be, a database of terrestrial pagers available in today's market was assembled with relevant details about each pager device recorded. The parameters recorded include the number of characters that can be sent in one message, whether the pager is one-way or two-way, whether or not it has a keyboard, its physical volume in inches cubed and its memory capacity. An end user terminal module was then subsequently defined and incorporated within the satellite simulation. This end user terminal module allows a system designer to define his or her ideal pager characteristics and obtain the estimated cost and one time activation fee that such a pager would merit in US 2002 dollars. The suite of characteristics decided upon for the end user terminal for the proposed satellite system is a pager that can send messages with up to 100 characters, (note that for such an end user terminal it would still be possible to send an SMS of the average 160 character length, it would just be broken up into two messages. Hence for a pager such as this the user would be charged for sending a "message" whenever up to 160 characters are sent to another user.) can send and receive messages (i.e. is two-way), has a virtual keyboard that lets you type messages on the screen, a volume of 1 – 4.9 inches cubed and a memory capacity that can store up to 5kb of past sent and received messages. In general, these characteristics should be satisfactory for the needs of the intended market group.

Averaged across many different types of pagers and system providers, such a pager as described in the aforementioned paragraph would have a unit plus one time activation fee cost of approximately $38.70. The calculations used to arrive at this cost along with a more detailed description of the end user terminal module are elaborated upon in Section B.9 of Appendix B. Another important parameter is the cost to send and receive messages, this is an objective value resulting from the simulation and listed within Table 3.9 as the 'cost per year' parameter. The cost per year to send and receive messages is based on an informed estimate of the number of messages that would be sent per day by the average individual in the developing world. The ITU's Portable Internet report details that as at 2002, the Philippines held the world record for the highest amount of text messages sent and received daily. Filipinos send and receive an average of 20 messages per day. [ITU04] With 20 messages per day as the upper bound I surmised that a nominal value of 10 messages sent and received per day was a conservative nominal estimate for the activity level of the average potential users of the proposed paging system. At this activity level, the cost per year to send and receive 10 messages per day ranges between $0.44/year and $387.94/year as illustrated in Table 3.9. Note that these values do not include a profit, thus each respective operator would add his or her desired profit margin.

The value for the cost per year to send and receive messages is added to the cost of the end user terminal to provide the minimum cost to the user for utilization of the service. The green vertical line in Figure 3-5 represents the value of the sum of both the cost of the described two-way pager plus the cost per year to send and receive messages for the Pareto architecture chosen to be most efficient. Figure 3-5 illustrates that if there were no limiting capacity constraints, at this cost approximately 2.75 billion of the 3.3 billion people in this developing world region would be able to afford the service.

The third line within Figure 3-5 represents the maximum number of subscribers of the most 'ideal' Pareto architecture filtered from the simulation's resulting Pareto front. The number of subscribers parameter is calculated from the capacity of the system. For this analysis the most 'ideal' Pareto architecture could support a subscriber base of 81,259,200 million subscribers where this value represents the number of subscribers limit for this SMS based system as indicated in Figure 3-5. Section B.10 of Appendix B contains a detailed description of how this 81,259,200 million subscribers value was calculated. To inform the selection of the most ideal architectures, the objective values most applicable to the needs of the developing world were analyzed. As such, the LCC, capacity and cost per year to the consumer for both utilizing the service and purchasing the end user terminal were compared to choose the most 'efficient' systems.

The cost per year for use of the paging service is a parameter derived from the multiplication of the cost per message parameter (which is an objective variable resulting from the simulation), the number of messages sent per day and the number of days in a year. From Table 3.9, design number 8 was chosen as the most 'ideal' system. This system provided the best ratio between LCC and total number of subscribers served as can be seen by comparison against the other Pareto designs in Table 3.9. This design was also the one with the highest capacity and lowest LCC among the Pareto designs in Figure 3-4. For systems such as this Pareto design number 8, the information for which is repeated in Table 3.11, compared to the cost of the end user terminal (i.e. \$38.70) the cost per year for sending and receiving messages (\$1.03 for design number 8) proved negligible. Hence, efforts of design for affordability should focus on the design of cheap satellite end user terminals.

Design Number (from Table 3.9)	Total Number of Subscribers (-)	Cost per year for use of Paging Service (US $)	LCC (US billion dollars)
8	81,259,200	$1.03	0.58

Table 3.11: The most efficient system filtered from the Pareto Optimal Designs

The implications of the information shared by the three lines plotted within Figure 3-5 are elaborated upon in the next section. Post processing can also include sensitivity and uncertainty analysis and this is recommended for future work to gain a greater understanding of the Pareto designs and how changes in the design vectors affects the behavior of the designs.

3.6 Implications of Results of System Architectural Trade Space Exploration

Figure 3-5 illustrates that with the currently available satellite communications technology the number of subscribers parameter calculated for the most 'ideal' Pareto architecture would serve 2.46% of the region (or 81,259,200 persons) with a cost to the user of approximately $345 per year. Thus while in its current instantiation the proposed system would not address a significant proportion of the defined developing world population, the proposed system could deliver affordable connectivity for small developing countries and populations in abject poverty with no alternate means of communication. Also as seen in Table 3.11, the LCC of this proposed system would be 580 million US dollars which is orders smaller than the LCC of existing satellite systems such as Iridium and Globalstar which are on the order of 3 to 6 billion dollars. This is a positive move in the path towards design for affordability.

Hence the analysis carried out in the trade space exploration process indicates that given what people can afford, the simulation's resulting Pareto optimal architecture has constraints on capacity and subsequent number of subscribers that would render the proposed system out of the price range of the majority of inhabitants within the developing world. Hence the constraint on number of subscribers for the proposed system does not match the demand of those within least developed regions within the demarcated equatorial zone, generally speaking.

In order to have a system such as the suggested one be feasible to a larger fraction of people within the demarcated zone, satellite engineers need to develop a system that can facilitate higher capacities at lower costs. Otherwise systems such as these will never realize their possible potential to render connectivity to those who stand to benefit the most from the delivered applications. The level of current technical ability within the satellite industry to provide low cost and reasonable capacity satellite systems is still worthy of sufficient additional research and development. This is not to undermine the connectivity that the proposed system has been shown to be able to deliver, but this analysis shows precisely that a serious commitment to design for affordability from the satellite community is imperative and needed to bridge the digital divide.

In 1988 dollars, for $1000 or less, Orbcomm offered a communication device that offered GPS signals with a short data messaging capability, allowing a customer to transmit location and a message from any location on earth. [JAF88] Compounded by the effects of inflation over the now 17 years since 1988, such a cost for an end user terminal is unambiguously out of the reach of the average person in the developing world. Hence there is a very real need for research to also surround the development of affordable end user terminals which would ideally rely on renewable energy as a power source. Renewable energy for end user terminal units should also be a strong area of research and development as access to electricity is often unavailable in the regions of concern. Research and development should also surround the manufacture of alternative keyboard/icon concepts for end user terminals for the illiterate, along with research on how these end user terminals can be made as sturdy as possible to withstand harsh environmental conditions such as rain, sand and other conditions common to the demarcated equatorial band.

Chapter 4

Re-engineering the Policy Framework of Satellite Systems

In the multifaceted arena that is satellite communications, a revolution in engineering design in which system designers design primarily for affordability is a necessary but insufficient requirement to realize the potential satellite communications technology has to provide a low cost means for realizing telecommunication services. In order to realize the objective of the fulfilling of public sector objectives through widening access to information and communication technologies, reducing costs associated with the policy and regulatory realm is also an absolute necessity. These costs take the form of economic, time related and productivity/potential reducing costs.

Reducing costs that arise specifically because of the nature of current national regulation is unlike the technical recommendations of Chapter 3, within current reach of the Administrations of many countries within the developing world. Lower regulatory and policy related costs will increase the affordability and hence tangibility of satellite based social services for the most needy. Another effect of lowered costs is that sales would also increase which would result in increased user volumes and hence greater economies of scale. This would then subsequently lead to additional cost reductions. Hence the possible effect of 're-engineering' the policy and regulatory framework of satellite systems is not to be undermined and would have a significant positive impact on the satellite industry.

In the early 1960s the USA through the Communications Satellite Corporation (COMSAT), formed as a result of the Communications Satellite Act of 1962, [DJW] established the need for a public monopoly organization for the provision of basic telecommunications services using advancements in satellite technology which were taking place at the time. [BN94] This was the motivation behind the creation of the INTELSAT international organization. At that time, administering telecommunications via a monopoly structure made sense as there was a vision of a globally unified system wherein a single system such as INTELSAT serves society's needs. This philosophy of approach stemmed from the combination of high infrastructure costs, network harmonization requirements and the requirement to provide universal service, all factors which led to telecommunications becoming a natural monopoly. [ST94] In this setting regulation was simply a matter of taxing generous profits and enforcing universal service obligations. [ITUD04]

However, today, more than 40 years since the catalytic changes of the early 60's, the satellite industry's policy and regulatory climate has taken on an entirely different character. The Policy structure has now made encouraging changes in tide towards liberalization and commercialization in satellite services and applications, first in developed countries and hopefully with time in developing countries also.

Consequently, it is important to now take stock and ask questions such as: what is the nature of the current policy and regulatory framework? Is it valid to assume that the models which were built up around telecommunications monopolies and unified global systems are no longer valid frameworks for the new millennium? Is the current framework possibly influencing satellite systems being out of reach for the developing world? What aspects of that framework are obstacles to the growth of satellite communications for the developing world? What policy changes need to be made and what are the best new national, regional and global processes and mechanisms for regulating satellite communications to affect long term sustainable development? How can concerned administrations encourage the widening of the scope of possible communication satellite applications to realms such as telemedicine and tele-education? These key questions related to the policy structure of satellite systems are addressed in the sections below.

4.1 Current Policy Framework of Satellite Communication Systems for the Developing World

Today, "the rules and procedures that make up the world of satellite communications are in the midst of change and even turmoil." [JP04] The rules that worked for the satellite industry in the past when telecommunications was squarely in the hands of state-owned monopolies are not the rules that will affect productivity today. During the 1980s the satellite communications industry experienced significant change. There were certain key forces that led to this change. The efforts within the United Sates government and private sector to engender competition and deregulation of the US telecommunications industry was one significant marker along the path of change and an important instigator of liberalization in the international policy framework of satellite systems. Another key step in this liberalization process was the move toward specialization in terms of high powered satellite systems with consequent lower cost demands on the ground from earth stations. The emergence of the regionalization of satellite systems (i.e. 'region' specific systems such as PanAmSat and Arabsat) also played a role in loosening the tight grip of a unified monopolistic approach to the regulation of satellite systems. Specialization also came in the form of the establishment of fixed, mobile, broadcast and radio determination services, these types of specialization were also key forces of change that occurred in the 1980s. [JP04]

As a result of these pioneers who facilitated this movement towards liberalization and competition in satellite services, the current regulatory and policy schema is one in which there is encouraging competition spreading into regions like Asia, Latin America, Africa and other traditionally developing regions. [ITUD04] Administrations within these countries are able to model their competitive frameworks from best practices learnt from the pioneers. However these changes in the policy framework have brought about new challenges and opportunities which undoubtedly require a review of the policy and regulatory framework that dictates the future direction of satellite technology.

Across the span there are now numerous varieties in how the satellite industry is regulated, as a result of the emergence of competition. It was stated earlier that across the globe, a wide variety of satellite regulatory schemas exist, this is because in some sovereign states a monopolistic framework still reigns true while in others there is fully operational competition with no unnecessary regulatory obstacles to new market entrants. Hence for the up and coming network operator it is necessary to contend with license requirements and procedures that may change considerably from country to country. Needless to say, this weighs heavily on resources of time, productivity and money.

There are encouraging signs however, the UK and Australia have successfully implemented regulatory agencies, the Office of Telecommunications (OFTEL) and the Australian Telecommunications (AUSTEL) agencies respectively, which are designed for open competition and which have already achieved measurable success. These are smaller operations that operate on the 'less is more' paradigm when it comes to regulation. To put in context, these organisations are about 25 times smaller than the FCC in the United States. [JP04]

Hence the predominant paradigm of today's policy and regulatory satellite communications agenda is one of far sweeping competition and a realization that there is a need to unify the regulatory standards across countries to harmonize standards as much as possible. An attendant positive effect of the far sweeping liberalization is that administrations in less developed countries are avoiding the need to have to agonize through the same slow, difficult chronological policy and regulatory steps that North Americans or Europeans went through. Instead, they are able to 'leap frog' traditional evolutionary steps and are now spending their energies on building internationally accepted principles and learning from success factors in the regulatory approaches embraced by more mature regulators. Specific current debilitating problems in the policy framework as concerns satellite communications for the developing world and attendant strategies towards solutions will be outlined in the next sections.

4.2 Is Current Framework Possibly Influencing 'Intangibility' of Satellite Systems for the Developing World?

The above discussion demonstrates that the old policy and regulatory models no longer apply today. And as in any other sector, once the rules of operation have changed, new tactics are needed to be effective. But how, if any at all, is the current framework acting in a debilitating manner as concerns extending the reach of satellite communications throughout the developing world? Firstly it must be noted that monetary assistance to aid telecommunications development from the World Bank and other regional development banks, INTELSAT, INMARSAT and other similar sources on average reduced in constant dollars from the mid 80s to the mid 90s. [JP94] And with a depressed world economy due to the terrorist attacks on the United States on September 11, 2001 and the ensuing wars in Afghanistan and Iraq, there is not much reason to believe the support would have increased appreciably at the turn of the 21st century.

To firstly set a context for the need to have the regulatory environment encourage satellite communication proliferation in the developing world, consider that in many developing countries, illiteracy rates are extremely high. In regions such as South and West Asia, for instance, only 1 in 10 females from rural regions have basic literacy skills, this is according to the Economic and Social commission for Asia and the Pacific region (ESCAP). [ST94] Unfortunately in spite of these stark needs, most parts of developing countries, especially rural regions, are still unabashedly cut off from existing national and international telecommunication services. Furthermore unlike in developed countries, terrestrial options are inadequate, extremely expensive and even sometimes non-existent, leaving no viable telecommunication solution for business leaders and everyday people within these regions.

In this process of the overhauling of the satellite communications sector from monopolistic to liberalized there are many obstacles to the wide application of this technology in developing regions. A knowledge gap which denies developing world authorities the ability to evaluate the opportunities offered by evolving technological advancement is one such obstacle. Also of concern are the existing inadequate financial resources and often overly excessive regulatory constraints.

Additionally, the very fact that the industry is in flux is a hamper. The recent two large LEO systems, Iridium and Globalstar, which were supposed to bridge the connectivity gap and bring personal communication benefits among other connectivity benefits to the globe turned out to be technological feats but economic failures. As such, the details of what works within the new model of international satellite communication competition and general operation is not yet very clear, even though billions of dollars have been spent on solutions that should have worked. This makes it difficult to get an all encompassing model for how to engender success in today's policy and regulatory climate. Furthermore, predicting future problems and trends in the field also becomes difficult, which may result in the satellite industry being deemed too risky a venture for resource strapped developing world countries. These factors play a strong role in the 'intangibility' of satellite communication systems.

4.3 What Specific Aspects of Current Telecommunication Policy and the Regulatory Environment are acting as Obstacles to Establishing the Proposed Satellite System?

By far, the most potent obstacle acting against the establishment of the proposed satellite system for the developing world is system cost. With regards to technical considerations, after implementing the satellite simulation of Chapter 3, recommendations were made for steps that should be taken by the satellite communications industry to design for affordability when envisioning future systems. However, as alluded to earlier, the problem does not solely lie in the technological realm, there are certain existing policy and regulatory standards which if not changed will render any possible technical design related cost reductions in satellite system design futile.

Reducing regulatory and policy related burdens so that those who wish to establish satellite businesses can have a realistic prospect of seizing commercial opportunities while also realizing public policy objectives is an objective that must be met with utmost urgency. It is reasonable to proffer that many opportunities may have already been lost to strengthen the link between the potential and current reach of satellite technology because of overburdening and unnecessary regulatory constraints. The following is a brief discussion of specific present policy and regulatory related constructs which are obstacles to establishing satellite systems within the developing world.

4.3.1 Harsh Regulatory Environment

Numerous telecommunications regulatory bodies today are subject to micro managing political interference, exacerbated by the fact that these same political institutions oftentimes also fund the regulatory organizations and this thus makes it difficult for the regulatory bodies to advocate for reduced political interference. Additionally, poor management and inefficient use of resources are also problems which plague the regulatory administrations within many developed and developing countries. Furthermore often to their own peril, many countries impose limits on the use of foreign mobile satellite terminals. It does not take much thought to realize that such a regulation hinders potential users from being able to reap the immense benefits of mobile satellite communications. [ST04]

Harmonized regulatory structures are of key importance from the viewpoint of satellite operators because of the extensive coverage area of satellite systems. By definition the services that satellite operators provide are often on a multi-regional scale which underscores the need for regulatory harmonization. Satellite operators thus depend on authorizations and spectrum allocations in each country in its coverage zone. If these authorizations take great pains to obtain, especially in a liberalized setting with many providers, then the prospects of realizing the benefits of satellite services would be severely retarded.

4.3.2 Dearth in Knowledge of Benefits of Satellite Technology

There is lack of knowledge and general awareness of the vast potential of satellite communications technology to act as a development enabling tool across a variety of public sector goals. Domestic education policies need to surround incorporation of teaching about the general benefits of information and communication technologies so that the proletariat will be convinced of the need to support and facilitate efforts to incorporate ICTs in their local agenda. Raising awareness levels across the private sector would also be beneficial as many private sector leaders do not even engage in meaningful discussions about the need to invest in satellite technologies for the developing world, as it is written off as extremely capital intensive and has been thus relegated to the public sector only. However private sector investment is critical to the sustained development of satellite communication technology.

4.3.3 Discriminatory Cost of Space Segment Access

Unfortunately, numerous regulatory bodies and many international satellite organizations (ISOs) use the satellite regulatory process primarily as a revenue generating mechanism. For instance, Signatories of the ISOs administer costly mark ups on their customers for access to the space segment they have governance over. This is counterproductive and goes against proclaimed intentions by these ISOs to propel the growth of the satellite communication industry. Furthermore, economic analysis shows that it is the consumer who ultimately bears the brunt of such fees and hence such costs translate to an additional tax on the already burdened consumer. Inordinate license fees imposed on satellite system operators are another way in which the current regulatory regime is acting as an obstacle to the growth of satellite systems for the developing world.

4.3.4 Rapid Technological Advancement

Rapid technological advancement presents real problems for the developing world as technologies that developing world make real efforts to incorporate into their national agenda are often not developed with the context of the developing world in mind. Hence there is a perpetual 'catching up game' that has to be played to reconstruct the technology in question to the needs of the populace. However if and when this is successfully accomplished there is normally another headlining technology about to come on stream that has the potential to leap frog the country to a greater stage of development. Hence speedy technological development presents a challenge to developing countries' abilities to adequately respond to these new changes. Some of the challenges are ensuring the right environment and developing applications that are in tune with the specific needs of the countries.

4.3.5 Conflicts of Interests

There is often times a conflict of interest caused by the fact that the owners and shareholders of the satellite systems, i.e. the Signatories, in many cases are also the ones promoting their own governmental systems which they may view as being in competition with many satellite systems' applications. Additionally, as at the mid-90s the major satellite systems (i.e. INMARSAT, INTELSAT AND EUTELSAT) had provisions for only one Signatory per member country. However in an era of increased liberalization, this provided for the difficult situation in which Signatories are empowered to allocate space segment capacity to national operators with whom they were in competition. Furthermore, with respect to EUTELSAT specifically, the Signatories' investment share in EUTELSAT is calculated as proportional to the country's total utilization of the space segment, however this total utilization parameter includes that of the Signatory's national competitors that share the system. [BN04]

4.3.6 International Administrations' Lack of Institutionalized Policies for Regulatory Infractions

Quite against what is allowed, China in the past launched a satellite called APSTAR 1 into the unregistered position of 131 degrees east which represented a new found problem for the ITU as the organization had no sanctions or tools to address this infraction. [JP04] Another troublesome infraction came in the form of Tongsat, the Friendly Islands Satellite Communication Company of the Kingdom of Tonga, "selling off orbital locations and filing 'copy cat' versions of satellite systems as they are presented to their national government." [JP04] At the time this infraction was a major source of concern to international regulatory agencies.

Pacific Star Communications, Incorporated ("PacStar"), a US based communications firm also caused concern and illustrated the need for greater policing when they attempted to establish satellite systems under a "flag of convenience" approach to enable them to gain rights to a convenient and low cost orbital assignment. [JP04] It is not to be believed that this problem of faulty governance is unique to the ITU or as a result of the lackadaisical implementation of their statutes. It turns out that similar to the ITU, the raison d'être for international satellite organisations such as INTELSAT and INMARSAT once included acting as a quasi-official standards making body for modulation techniques, error control and earth station characteristics. However a fate similar to that of the ITU befell them as the authority and global consensus potential of these organisations have eroded extensively.

These observations of the above paragraph underscore the fact that these institutions were created with a set of assumptions about how telecommunications in general and satellites in particular would best be regulated; and now the industry is operating under a different set of rules which render the original assumptions null and void. It is this mismatch in the world these organisations were premised on and the world that exists today that can act as an obstacle to the establishment and sustainable development of satellite systems under today's rules of operation.

4.3.7 Agencies Not Structured to Meet Today's Policy and Regulatory Challenges

At the root of the problem elaborated upon in the section preceding this one is the fact that many of the national and international units which are regulating and defining the policy environment for satellite communications were envisioned and structured when monopoly control was the order of the day. In the policy regime under which these organisations were formed, the telecommunications monopoly established the industry standards, set tariffs, and planned systems which were then ratified, regulated or controlled by the government. Often the regulating body was the Ministry of Communications or a similar authority which in effect resulted in the agency supervising itself. The possible problems associated with an administration reporting to and policing itself should be clear, but in addition these institutions are not well equipped to deal with an open competitive environment with ever advancing technologies and the need for ingenious tariffing and standards policies that can mean the difference between success and failure in today's marketplace. The "re-engineering" of the policy framework that needs to occur to enable these policy setting organisations to be effective and to facilitate the growth of sustained growth of satellite communications is elaborated upon in the next section.

4.4 What Policy Changes Need to be Made to Affect Sustainable Development in Regard to Satellite Systems (especially those Catered to the Needs of the Developing World)?

The World Bank's Information for Development international consortium wrote in early 2005 that "In the past few years, Information and Communication Technologies (ICT) for development initiatives have proliferated. Yet, rigorous field-tested knowledge about "what works and why" in ICT for development, and a deeper understanding of the enabling conditions and success factors in ICT-for-development initiatives, have been relatively scarce." [INFOD] This is especially true as it concerns the potential of satellite communications to bridge the digital divide. By and large satellite operators have not been enlightened as to the power of the development enhancing tool that is satellite communications.

There is a growing consensus in the development community that ICT can only become an effective and mainstream tool of poverty reduction and sustainable development if the supporters of ICT-for-development can provide more rigorous evidence, strategies, benchmarks, indicators, and good practices that are directly relevant to the core poverty-reduction and development priorities of developing countries. The literature search I conducted demonstrated a significant lacking in quantified rigorous support of the feasibility and tangibility of satellite communication systems catered exclusively to the developing world. The developing world has a strong role to play in bringing this information to the masses. Until such evidence and information becomes available satellite operators and possible investors will not be convinced of the tangible benefits of directing their efforts towards fulfilling public policy objectives.

For all the potential that satellite communications harbors to 'leap frog' many countries from the negative ramifications of poverty and effect sustainable development, I have not seen a commitment from the international administrative agencies to encourage current and future providers to assist in bridging the digital divide. With the licensing and spectrum authorizing power that these organizations have, steps could be made to incorporate incentives to providers who show a demonstrated commitment to realizing social needs across the world's poorest countries. Whether it is an increased probability of obtaining a license, increased license times or reduced licensing fees, there are a wealth of creative incentives that could be implemented to effect a solid commitment from the satellite communications industry to exploit the significant development promoting power the technology has. History has shown us that we cannot depend on altruism alone.

Additionally, in regards to the concern raised in the previous section that the ITU, among other international agencies, does not have stringent enough policies in place to deal with infractions, a restructuring and re-definition of the role of the ITU to establish clear and enforceable standards is in order. Currently, ITU standards are expressed as 'recommendations,' however in a setting where systems are vigorously vying to be established in a timely manner such 'recommendations' can lead to intersystem coordination processes taking years to resolve and this is unacceptable. Like the recently formed new age regulatory agencies OFTEL and AUSTEL, we need agencies that do more 'policing' than 'recommending' to avoid the time burden and the type of infractions detailed in Section 4.3. The first step to realize such an ambition would be to empower international organizations to be able to fine both governments and corporations that do not operate within the letter of established rules and procedures concerning the use of orbital space, frequency allocations, interference abatement methods and fair methods of competition.

Moving from the ITU to commercial based international satellite organizations, these ISOs have to be called to enact serious policy changes to affect the sustainable development of the satellite industry. For space communications there is a need to adjust to the new environment which means privatization of their capital forming structure, enabling direct competitive access to their space segment for all services (not just popular tried and true ones such as VSATs and DirectTV), and greater elasticity in the tariff setting process to reflect market scenario and costs. [JP04]

Mention was made earlier of OFTEL and AUSTEL as two examples of the new breed of regulatory agencies which have made successful strides to adapt to the new policy framework of communication systems. Unlike their predecessors, these agencies have not made it their mission to monitor ever tariff, service, and application within their domestic communication realm, but rather they work to expose any unfair or inequitable competition or infractions in their country's open access to the network. Infractions reported by customers, service providers or other stakeholders are duly investigated and serious penalties administered where infractions are confirmed. Penalties can comprise of fines in the millions of dollars or limiting the market access of the perpetrators. Pelton informs us that to date the evidence has shown that these agencies are succeeding at enforcing an equitable operating base. [JP04] The key point for other regulators to internalize is that an agency designed to keep watch over a competitive environment would operate differently than an agency designed to ensure that a monopoly does its job well.

Thus with regards to the serious violations mentioned in the previous section, the feasibility of International Trade Organizations or the ITU itself being authorized to penalize organizations and governments that violate the guidelines and procedures for international satellite communications is an urgently policy direction that must be pursued.

Increased private sector participation is vital to the sustainable development of satellite systems. In developed countries there are solid examples of private sector operators who have been key players in efforts to achieve universal service in their home countries. These investors would be willing to invest in the great potential that exists within developing countries; the investment climate has to be attractive however. Thus developing countries' private and public sectors must do all they can to weed out top level corruption and other investment hindering forces. Such actions would then create a setting that can attract private sector investment from operators who have successfully implemented public policy objectives elsewhere. As an example of the private sector getting involved, in Thailand, educational television services by satellite are provided through a joint initiative between the Ministry of Education and the private sector. [ST04] More and more, public-private sector partnerships are emerging as feasible means by which to enact telecommunications development.

The high cost of obtaining operations licenses and other regulatory necessities was raised in Section 4.3 as one of the lead obstacles in the path of establishing satellite systems for the developing world. Hence due consideration and efforts must be put in place to reduce barriers to entry for satellite communication operators who seek to enter the satellite market. The goal of universal service, especially to rural and remote areas must always be the yard stick against which regulators measure when making licensing decisions. It goes without saying however that it is important that appropriate conditions are met and sustainable viability proven before licensing is granted.

Another important change that must occur is a move from viewing satellite technology as a competitor to terrestrial systems. Still today many governments view this technology as a threat to the terrestrial systems they have invested in heavily. This thesis thus seeks to illustrate that satellite technology should be viewed as an enabler of development for regions that terrestrial telecommunications has not yet been able to service. Section 2.3 illustrated that for rural regions without the existing infrastructure to enable the development of wired communications, and for which the implementation of such wired infrastructure is often impractical due to costing, time of implementation and difficult terrain, satellite systems offer real cost advantages over terrestrial mobile systems. In contrast to satellite systems which are not dependent on the density of their regions of coverage, the cost per user of terrestrial systems is adversely affected by the spatial layout of the traditional low population densities of rural regions.

Even for regions currently served by telecommunications services, governments and other decision makers should be made to see that satellite technology can also deliver certain social services such as telemedicine, tele-education and disaster relief at a rate and to a coverage area that terrestrial communications cannot currently measure up to. As such, satellite communications should be viewed as a necessary aspect of the solution to the digital divide conundrum with efforts being made to have this technology work in a symbiotic relationship with terrestrial telecommunications technology rather than as a competitor.

As an example, developments in satellite technology have brought about the growth of VSAT systems. Unfortunately the growth of these inexpensive and high potential systems has been hindered by restrictive regulations in many developing countries. [ST04] Taylor informs that this is mainly due to there being a perception that VSATs compete directly with the mainly terrestrial, telecommunications infrastructure present in these countries. Many countries are also wary of the security concerns that the introduction of such systems, often from foreign providers, introduce. However if this technology is to be allowed to take its rightful place amongst the ranks of development enablers, the appropriate facilitating framework must be established. One avenue to pursue is the creation of licensing procedures and type approval to ensure the necessary safeguards for these new emerging technologies. At the same time, in order to be granted a license these operators should not be allowed to focus exclusively on the top niche markets in the developing countries they seek to serve.

Yet another debilitating obstacle mentioned in section 4.3 is that of the nature of the ISOs Signatory function and conflicts of interest that may arise. This goes hand in hand with the limitations in direct access to space being experienced by satellite operators. As the previous section detailed, the problem arises from the basic Agreement establishing the ISOs in which signatory Parties are required to appoint a Signatory, usually the public telecommunications operator, as the sole provider of space segment capacity in their country. The Agreement dictated that all requests for space segment capacity come through the Signatory. While this would have been appropriate in a monopolistic schema, in a competitive environment this arrangement could raise serious conflicts of interest. The crux of the problem being that the Signatory is empowered to determine the cost of access to the space segment for its competitors. This is the primary reason why there have been lobbies for direct access to space segment by satellite system operators. There has also been an encouraging strong push by satellite operators to be able to approach any space segment provider for their requirements. While there have been some encouraging developments in this regard, all ISOs must seek to comprehensively address these concerns.

Let us now take our assessment of needed policy changes to the regional level. On the wider regional level, cross country cooperation is a must if the potential of space communications is to be realized in developing countries. This cooperation should focus on, amongst other things making the technology affordable and relevant for the neediest amongst us. A model example is the agreement arrived at in Beijing China in September 2004 wherein Ministers of the Asian and Pacific region agreed on a regional strategy for cooperation in space applications for sustainable development. [ST04] Key aspects of the adopted policy include the pooling of resources, the integration of space applications in the development planning stage, and the creation of international networks to raise awareness amongst the proletariat in their regions of the potential benefits of satellite technology. In this age of mobile satellite systems which depend on global and regional harmonization for their commercial viability, this is a sterling example of a group of nations committing to regional cooperation and its attendant benefits.

In summary, the overriding theme from the above discussion is that satellite regulators must seek to do only that which is truly and minimally necessary to serve their purpose. In so doing here are five guiding points provided by a recently issued ITU regulatory report entitled: Report on Satellite Regulation in Developing Countries [ITUD04], which all policy and regulation setting bodies would do well to incorporate:

a) Uncomplicate the regulatory process. For instance, if there is no need to differentiate between domestic and international satellite services then do not do so.
b) Regularly review the current regulatory and policy framework to ensure it matches the present context. Be aware that the regulatory framework in place today may be defunct in five years time.
c) Be extremely aware of hidden costs – especially time. Regulatory structures that are unnecessarily complex hurt operators the most with regards to time.
d) Resist the temptation to use the regulatory purpose for purposes other than regulation. The most specific concern here is its use for revenue generation.
e) Create through the medium of the worldwide web for example, a nearly immediate, inexpensive and transparent public platform from where access to each Administration's satellite regulations is provided. Not only would this attract investment but it would also reduce the Administrations' administrative burden.

4.5 How Can Involved Stakeholders Encourage the Widening of the Scope of Possible Satellite Communications Applications?

Given that the existing cost structures of current ISOs are a significant hamper to basic communications applications reaching the disenfranchised, then one can imagine that sophisticated applications such as telemedicine and tele-education are even further out of reach. However compared to any other time in history the satellite communication sector is better equipped today than it ever was to meet this challenge of the widening of the scope of its applications. Certainly all the strategies mentioned in section 4.4 hold, however, there are a few other strategies and information specifically catered to encouraging the widening of the scope of applications to meet public policy objectives that should be illuminated.

The ITU's regulatory report [ITUD04] informs that revenues from satellite manufacturing services, launch, and ground equipment have demonstrated unwavering growth from 1996 to 2003. This growth which is estimated to have reached US 91 billion dollars in revenue in 2003 is progressing faster than most other industry sectors, even more than many other successful sectors in the communications industry in general. Furthermore, it is in the area of satellite services that the most impressive growth has been recorded. The latest Figures project global revenues of the satellite industry to top US 94.7 billion dollars in 2004 and to total as much as 127.2 billion dollars by 2010. [ITUD04]

Some fraction of this appreciable revenue generated by the satellite industry should go to research and development directed towards increasing access to telecommunications services throughout the world via widening the scope of applications which bring needed social services to areas currently suffering from a dearth of such services. Such actions would benefit all stakeholders as in today's connected global village where actions in one region have direct reactions and consequences in other regions, we can no longer continue to differentiate the plight of the world's poor from the world's global plight.

Fundamentally, real improvements in the economic, educational and health standards of the world's marginalized, filtrates into an increase in social equity and basic security for us all.

There have been positive recent signs that the satellite industry is embracing the need to create a more favorable regulatory framework which could eventually lead to the widening of the scope of satellite applications. A recent global survey on satellite regulation in developing countries compiled by the ITU in their 2004 regulatory report [ITUD04] confirms that administrators are moving towards a host of regulatory directions designed to enhance competitiveness. Some of the initiatives confirmed by the survey to already be in place in some regions are:

- "Open Skies" or less cumbersome requirements that have to be met in order for the landing of foreign satellite services to be permitted
- A relaxation by domestic administrations of the regulatory stronghold governing satellite-based service provision, which might eventually spill over into the international arena
- Greater use of mobile satellite terminals
- Relaxation of the obligation to provide local satellite infrastructure (where local satellite architecture refers to the creation of a hub or teleport as a licensing condition for networks) and
- Reducing disconnects in satellite regulations within regional and sub-regional groups

Lastly, for individuals such as myself who see promise in establishing new satellite communications systems specifically catered to the developing world it is of utmost importance that the legal and regulatory climate does not discriminate in favor of existing service providers, or otherwise restrict the number of independent service providers that are allowed to provide satellite services to the populace. The literature search in this area has given me reason to believe that such discrimination against 'new-comers' has existed in the past. Discrimination of this form makes little sense because as in other industries, strong competition between a large number of service providers promotes investment in infrastructure, provision of new services, improvements in service quality and the ultimate benefit to the consumer of lower prices.

With the combination of the above recommendations and those of section 4.4, it is hoped the way can be paved for the implementation of ingenious and needed applications stemming out of satellite communications technology.

4.6 Summary

Several questions were posed at the beginning of this policy analysis. One point to note firstly is that while the many issues that were raised are certainly relevant to LEO systems, there are still missing links in the satellite policy and regulatory framework concerning how LEO systems such as that proposed in this thesis would specifically be impacted by the current policy and regulatory climate. This analysis sought to make a contribution to bridging that gap in the literature.

This analysis showed that the current regulatory framework is in flux with some national telecommunications policy frameworks ranging from staunchly monopolistic to quite liberal. There are now a few forward thinking administrations that do not oversee their regulatory frameworks on the level of fine detail of their predecessor administrations but rather apply a more 'hands off' mode of regulation commensurate with the increased levels of competition in their countries. These liberalized administrations act more in a 'policing' role bringing punishing infringers, rather than in the more 'micro management' like model that was more common to the monopolistic schema.

It was shown that the current policy framework is undoubtedly influencing satellite systems being out of reach for the developing world. Though there have been noteworthy achievements, inequitable access to space segment and an underlying belief that mobile satellite applications (such as that which would be produced by this proposed system) act in competition rather than in a symbiotic relationship with existing traditional systems, continue to be major blockades in the path of the development of LEO systems.

A demonstratable commitment to having the regulatory process not serve primarily as a revenue generating mechanism along with specific strategies for opening up access to space segment for potential satellite system operators are outlined among others as changes that must occur in the regulatory and policy framework. Such changes would help to ensure the long term sustainable development and would significantly aid in realizing the potential of satellite communication systems.

Chapter 5

Conclusions and Recommendations for Future Work

5.1 Summary of the Current Research

The purpose of this research was to assess the technical, economic and policy-centered feasibility of a proposed satellite communications system for the developing world. The developing world being defined as the equatorial band of 30° north to 30° south latitude. The research process was divided into three stages, each of which is summarized in the sub-sections that follow.

5.1.1 Summary of Background Demographics Presentation and Economic Analysis

The first stage of this research involved the presentation of a comprehensive database of the developing world which was assembled for the purposes of this research. Information and local context was given for important factors relating to a country such as a concise history, its geography, people, government, economy, communications, transportation, religions, military and transnational issues. Using the information provided in the CIA World Factbook [CIAWFB] an extensive database was put together to firstly get a working definition of the developing world and then to explore other key aspects of the developing world that would inform the development agenda of this thesis. A summary of the world database is shown in Appendix A.

During this analysis, the framework and supporting data is provided to support the need to 're-engineer' satellite system design for affordability. The development goals of the international development arena around information and communication technologies (ICTs) in general are first presented to set a context for the analysis. Telecommunication means that currently exist to provide connectivity are then explored along with a discussion of the past and current commercial satellite system industry. Solid evidence of the expanse of the digital divide which is largely based on an underlying income divide is subsequently analyzed. The results and data presented provide a sound rationale for why a 're-engineering of satellite system design for affordability' revolution is necessary to support efforts to bridge the digital divide.

5.1.2 Summary of Technical and Economic Feasibility Study

The second stage of this research involved a formalized technical and economic feasibility study which took the form of a comprehensive MATLAB based trade space exploration. The first stage of this process was to implement a computer simulation originally created by de Weck and Chang. [dWDC03a] This process consisted of the following six steps:

1. Choose the elements and bounds of the architectural design space inputs which include the design vector **x**, constant vector **c**, policy vector **p**, and requirement vector **r**; and outputs that include the objective vector **J**, and benchmarking vector **B**.

2. Build the mapping matrix between inputs and outputs and subdivide the problem into modules which match the system's physical and functional characters. Define clear cut interfaces between modules.

3. Implement and integrate the modules based on technological-physical, economic and policy relationships such as constellation geometry, astrophysics, communication theory, cost estimating relationships which implements the economic analysis and market estimation. Implement the individual modules and test them in isolation from each other. Then integrate the modules into an overall simulation.

4. Benchmark the simulation against the data of reference systems. Tune and refine the simulation as necessary (Loop A in Figure 3-1).

5. Conduct a systematic trade space exploration using a full factorial run that covers the entire possible range of design variables.

6. Identify and post-process the Pareto optimal set. If no acceptable Pareto optimal solution is found, the design space needs to be modified (Loop B in Figure 3-1). Once the Pareto optimal solutions are arrived at, extract a subset of Pareto optimal architectures that are non-dominated for further study.

As a result of undertaking these 6 steps shown above a simulation for the proposed satellite system was developed that had reasonable fidelity. A full factorial run produced 276 designs of which 16 were Pareto optimal. These Pareto designs were studied for their technical and economic feasibility for the intended developing world market.

5.1.3 Summary of Policy-Centered Feasibility Study

The final and third stage of the research involved assessing the 're-engineering' that needs to take place within the policy and regulatory framework of satellite communications systems. In order to successfully affect the sustainable development of satellite systems which can increase access to social needs, attention must be given not only to changes that need to occur in the technical realm but also to changes that must occur in the policy and regulatory realm. This is especially important given two reasons, firstly, the policy framework is currently in a state of change needing new approaches to keep it buoyant and relevant. Secondly, the long term feasibility of systems such as the one proposed in this thesis can only be achieved if necessary changes are made in both the technical and policy realms as successes in each realm independently are necessary but insufficient aspects of the solution to bridging the digital divide. The necessary and sufficient conditions to facilitate making real strides in addressing the problem of the digital divide include, inter alia, technical, policy-related, economic and cultural considerations.

Consequently, as concerns the policy realm, this stage of the research is where we pause and take stock and ask questions such as: what is the nature of the current policy and regulatory framework? Is it valid to assume that the models which were built up around telecommunications monopolies and unified global systems are no longer valid frameworks for the new millennium? Is the current framework possibly influencing satellite systems being out of reach for the developing world? What aspects of that framework are obstacles to the growth of satellite communications for the developing world? What policy changes need to be made and what are the best new national, regional and global processes and mechanisms for regulating satellite communications to affect long term sustainable development? How can concerned administrations encourage the widening of the scope of possible communication satellite applications to realms such as telemedicine and tele-education? These key questions related to the policy structure of satellite systems are addressed in the third stage of the research. The analysis points to an urgent need to have the policy and regulatory framework be commensurate with the present reality of the satellite industry.

5.2 Conclusions

Given the research conducted in this thesis, the following conclusions can be drawn:

5.2.1 Demographic Background and Economic Analysis

In summary, the data gleaned from the developing world database points to two major conclusions. Firstly, a satellite system specifically developed to address the connectivity inequities of the developing world as proposed in this thesis is an immediate and extremely needed solution to a continuously exacerbating digital divide inequity. Secondly, there are non-trivial economic inequities which underscore the fact that developing world countries would be afforded enormous advantages through the introduction of a communications medium that is not dependent on the country's specific infrastructural maturity state and which is affordable and applicable to extremely marginalized communities. Hence the developing world has a yet untapped, immense potential to be a bustling market base for well researched connectivity applications. With informed hindsight on the part of system designers to ensure the satellite system's applications are not technologically overly elaborate and provide the needed connectivity at minimum cost, this thesis's proposed system would make significant inroads in increasing access to many of the world's most basic social needs.

Of particular note is the fact that as shown in Figure 2-9 and Figure 3-5, there is a significant drop off in the number of people that would be able to afford a satellite system when the price for the end user terminal plus service costs vary between \$60 and \$90 in 2002 US dollars. At a pricing of \$60 approximately 2.3 billion people would be able to afford the communication service while at a pricing of \$90 only approximately 1.4 billion people would be able to afford the service. Hence an increase of only \$30 has caused a sizeable shift in the number of people in the demarcated range that would be able to afford a given service. This underscores the need for design for affordability in satellite and end user terminal design.

The current satellite system industry is technologically mature but yet to make impressive strides in the social good, policy and economic contexts. Satellite system design of the future must be revolutionized such that system designers endeavor to design for a multiobjective problem for which the objectives are:

- affordability for market bases most in need
- basic technical capability to carry out desired connectivity
- efficient design within current policy context
- adherence to the regulatory framework
- seamless incorporation (as is possible) within desired region/s of coverage's already existing mode/s of communication and lastly,
- design for sustainability of envisioned system

5.2.2 Need for Design for Flexibility Approach in Regard to Key System Parameters

The economic failure of Globalstar and Iridium is largely due to overestimation of the intended market size for the two systems. It is important that when modeling important parameters such as the number of users and the user activity level that extreme caution is taken to design for flexibility should those estimations be off the mark. It is also important that concerted efforts be made to consider competing technologies that may sway some of the envisioned satellite system's potential users once the system comes on stream, which may be as much as a decade onwards from the design phase.

5.2.3 Modeling Complex Engineering Systems is Feasible and Necessary

This research has demonstrated that even for complex engineering systems with high level economic analysis built in, system modeling utilizing a multiple modular framework is feasible. Irrespective of certain simplifying assumptions as detailed in Chapter 3, the system benchmarks reasonably with established satellite systems such as Orbcomm in this case and is quite comprehensive. Successful implementation of the system model lends to a platform from which a trade space exploration can be enacted which results in insightful information about both the design space and costs to be incurred for the envisioned system.

5.2.4 Cost Considerations – Important Design Objective

Unlike the analysis carried out for previous major satellite systems, cost considerations, more specifically life-cycle cost considerations, need to be integrated as a design objective from the very outset of the design process. As Chang details, lack of consideration for cost early in the design process could be the reason why some of today's real world systems are not Pareto optimal. The analysis he conducted illustrated that the Pareto optimal designs for Globalstar and Iridium that have similar capacities to the two systems, have costs around $2 billion dollars, in contrast to the $3.3 billion of Globalstar or the $5.7 billion of Iridium. [DC04] Chang shares interesting insight when he states that the tendency to not consider cost early in the design process could be a ramification of the "spin off" model that characterized technological development in the United States during the Cold War era. In the "spin off" model technologies were first developed for defense purposes, and then subsequently transferred to the civilian commercial market. The history of satellite systems supports this phenomenon as it is a known fact that many of the civilian satellite technologies we enjoy today first premiered as space technologies utilized in defense capacities.

Especially for systems such as the proposed satellite system, cost considerations need to be integrated in the design process from the initial design phase. Affordability has to be of primary concern in the design process. The way the satellite simulation in this analysis goes about incorporating cost considerations is to make cost one of the dimensions in the objective space, and thus the Pareto optimal designs in this objective space would have optimized, inter alia, for cost as illustrated in Chapter 3 of this thesis.

5.2.5 Technical Changes Needed to Make Proposed System Feasible

With the currently available satellite communications technology the number of subscribers that the simulation's 'ideal' Pareto design would serve amounts to 2.46% of the +/30° region (or 81,259,200 persons) at a cost to the user of approximately $345. Thus while in its current instantiation the proposed system would not address a significant proportion of the defined developing world population, for small developing countries and populations in abject poverty with no alternate means of communication, the proposed system could deliver affordable connectivity. Also as seen in Table 3.11 the LCC of the Pareto architecture of the proposed system would be 580 million US dollars which is orders smaller than the LCC of existing satellite systems such as Globalstar and Iridium which were on the order of 3.3 to 5.7 billion dollars respectively. This is a positive move in the path towards design for affordability.

Hence the analysis carried out in the trade space exploration process indicates that given what people in the developing world region can afford, the simulation's resulting systems have constraints on capacity and subsequent number of subscribers that would render the proposed system out of the price range of the majority of inhabitants within the developing world. Hence, generally speaking, the constraint on number of subscribers for the proposed system does not match the demand of those within least developed regions within the demarcated equatorial zone.

In order to have a system such as the suggested one be feasible to a larger fraction of people within the demarcated zone, satellite engineers need to develop a system that can facilitate higher capacities at lower costs. Otherwise systems such as these will never realize their full possible potential to render connectivity to those who stand to benefit the most from the delivered applications. The level of current technical ability within the satellite industry to provide low cost and reasonable capacity satellite systems is still worthy of sufficient additional research and development. This is not to undermine the connectivity that the proposed system has been shown to be able to deliver, but this analysis shows precisely that a serious commitment to design for affordability from the satellite community is imperative and needed to bridge the digital divide.

5.2.6 The Policy and Regulatory Framework of Satellite Systems

If we are to meet the necessary call of realizing the full potential of satellite communications technology, developing countries and ISOs must review their present policy and regulatory frameworks to remove those constraints that create bottlenecks in the full exploitation of satellite technology for development and are no longer relevant given that the present policy framework has the industry moving beyond monopolies. A minimalist regulatory structure should be enacted that does not micro manage the industry and its newly liberalized scheme which involves numerous operators but rather acts as a watch dog for infractions against set rules and policies. This will be to the benefit of all involved stakeholders - the service providers, the equipment suppliers, and most importantly the end user.

5.2.7 New Thought Structure Needed within Developing World to Enact Economic Development

Developing world leaders must ensure they are astutely aware of the fundamental changes that are overtaking their regions as a consequence of economic globalization. Let us take the Caribbean region for example. The World Bank [WBNK] recently issued a timely report entitled: 'A Time to Choose: Caribbean Development in the 21st Century', the report is based on a honest premise – for developing regions such as the Caribbean, economically, things cannot remain the same.

As Jamaica's leading newspaper, The Gleaner, states, "It (the report) proposes that the region eschews the trade preferences that have been an economic crutch for the past 30 years. Despite their apparent advantages, these trade preferences have left the region with a shrinking share of the European and North American markets. The bank sees benefits from offshore education, health services and information and communication technology, which it suggests are potentially strong areas of growth for the island states.

Getting regional leaders and policymakers to make a move along this path may not be so easy. Ignoring the obvious - or not seeing it - in the changing economic paradigm, they continue to determine economic growth by outdated measurements. In those areas in which governments claim to have accepted the increasing economic value of information and communication technology, there appears to be myopia and confusion. In Jamaica, the technology minister, who once spoke of the need to create a computer literate and technologically-advanced society, was silent when his colleague minister of finance made the retrograde step on re-imposing a tax on computers.

The World Bank accepts that the new economic route for the region will not be easy. It sees hurdles in sub-standard social services such as health and education, and the increasing dead-weight of intractable unemployment. There is concern that fundamental changes in economic policy could be hindered by repeated indications of petty parochialism and nationalism that are blind to the impact on small economies of economic globalization.

The global economy is changing rapidly and significantly. Caribbean economic minds must start thinking out of the domestic box and combine their efforts to make beneficial use of new challenges (such as the incorporation of information and communication technologies), that bring new opportunities." [JG05]

5.2.8 Role Satellite Communications Can Play in Development Process

New digital technology and explosions in multimedia and broadband services underscore the immense potential satellite communications technology has to fulfill as yet unmet development goals to a coverage area and within a time span as yet unrivalled by terrestrial systems. In developing countries a necessity for socio-economic advancement is integrated rural development. An essential requirement in this integration process is communication infrastructure, within which satellite communications has a leading role to play. The technology has the potential to leap frog marginalized regions many rungs up the ladder of development and the international satellite community must capitalize on this opportunity to better the plight of our fellow human beings.

It is important to remember however that ICTs can only be a useful enabler of development if it is introduced in a meaningful, relevant and structured way. Without the training of the target users, access to the technology in an appropriate context, a well-organized plan for integration into the existing system (or plans for the reform of the existing system), and a vision for the way forward, ICT will be just another missed golden opportunity – which is too high a price to pay.

5.3 Recommendations for Future Work

To continue to carry this necessary research forward, the following recommendations are made for future work:

5.3.1 Fine Tune the Market Module Expressly for the Needs of the Proposed SMS System

The Market Module is a key module for the analysis in this thesis. It outputs the number of subscribers provided by the satellite system per year, the total air time of the system, and the total amount of data transmitted throughout the system's lifetime. The inputs of the module are, among others, the number of users supported per satellite, the Earth land area and Earth surface area of the coverage area of the satellite system. To fine tune the analysis further it would be best to obtain values specifically pertaining to the context of a messaging system for the +/- 30° equatorial band, for the number of potential subscribers to the system and the yearly increment of subscribers. The value used in the thesis was a market researched value for the number of subscribers to low bandwidth satellite systems (i.e, user data rates less than 50 kbps).

5.3.2 Refine the Design Space

It would be of merit to conduct a trade space analysis with a greater number of values for each design variable. This would facilitate a deeper understanding of the design space and possibly provide further Pareto points for analysis. However, because the trade space grows exponentially with the discretization, full factorial runs at high levels of discretization of the design variables may be extremely computationally intensive. At high levels of computational intensity, alternate optimization algorithms should be utilized in the process of obtaining the optimal solutions.

5.3.3 Use of Additional Objectives to Measure Merit of Designs

Within the research the "goodness" of each design is measured using the objective values of life-cycle cost and system capacity. However additional objectives can and should be used to ascertain which of the various resulting architectures are better than others. Total lifetime data flow or system reliability (which would have to be modeled and incorporated into the simulation) are examples of additional parameters that could be used to measure the "goodness" of the system designs.

5.3.4 Conduct More Rigorous Economic Analysis

Within the thesis, given the research conducted by Cook, [HC97] it was surmised that approximately 3 percent of a person's income would be focused on services, a reasonable fraction of which would be spent on communication purposes. Further research should be conducted to ascertain more decisive values for how much people in the developing world spend on communications services, especially in light of how much current mobile connectivity options are being embraced throughout the developing world.

5.3.5 Conduct Further Research Including Sensitivity and Uncertainty Analysis on the Pareto Designs

Sensitivity and Uncertainty analysis allows the system designer to gain an understanding for how changes in the design variables affect the objective vectors and the degree to which uncertainty perturbs the system. Further research in this regard should be carried out on the Pareto designs.

5.3.6 Obtain More Detailed 'Activity Per User' Information for SMS Applications

During the simulation analysis, given information on maximum SMS usage across the developing world today, it was surmised that a usage activity level of 10 messages sent and received per day was a fair assumption. This assumption should be refined through further detailed research into user messaging activity throughout the developing world.

5.3.7 Conduct Further Investigation on Pareto Font

There are certain seemingly redundant Pareto front architectures being produced by the simulation analysis as demonstrated in Figure 3-4 despite the use of a strong Pareto front filter. Further research should be conducted to confirm the reason for the production of these seemingly redundant Pareto designs since the strong Pareto front filter by all accounts was used appropriately. I have investigated this matter but found no anomalies that could have resulted in the production of extraneous designs. The further research in this regard should be aimed at presenting a set of Pareto designs that are all valid and which represent strongly non-dominated designs.

5.3.8 Develop Stakeholder Value Model

It would be of extreme value to carry out a quantified stakeholder value model analysis. This would be a dynamic analysis which would allow for a clear delineation of each stakeholder's needs and how these needs are being met. It also allows one to understand how different stakeholders map to others and the incorporation of 360° mapping allows for a comprehensive understanding of the system. Additionally, the process of the quantification of the stakeholder value model enables comparisons between stakeholders which may have once been obscure to be clearly identified and compared against others if necessary.

5.3.9 Develop Precise Geographic Models of Connectivity

Section 2.3 entails a discussion of the cost to provide connectivity in the capital of countries vs. more rural areas within these countries for four sample countries exhibiting different characteristics. The discussion was predicated on the stark change in population density which occurs when one moves from the industrialized capital of a country to the outlying rural regions. This stark change in population density often makes it economically difficult to provide terrestrial connectivity services to rural and sparsely connected populations. It would be of worth to develop geographic models of connectivity for the exact layout of the population densities in countries within the coverage area of the satellite system in order to analyze how this affects the cost of providing terrestrial connectivity mediums vs. satellite based connectivity mediums. Any differences in monolithic type country layouts vs. a group of islands (such as the Philippine archipelago), as concerns geographic models of connectivity should be researched and outlined.

Appendix A

Description of the World Database

As detailed in Chapter 2, a world database was assembled using the CIA World Factbook as an information resource. [CIAWFB] Pertinent information relating to this thesis was gathered and stored in a number of tables. The main aims of gathering the information were to firstly gain an in-depth knowledge of the demographics and significant defining information about each country, especially those in the developing world. For any researcher attempting to conduct an analysis of the impact information and communication technologies can have on development, it is of fundamental importance that time and energy be spent on getting to know the nuances of the area of focus well.

Some of the questions that should be asked are: what, if any, are the peculiar traits about the developing world region? What is their economic stance in real dollars? How do they measure up specifically with industrialized countries with regards to their telecommunications sectors? How stable is their government and thus the prospects for long term development, what are their main industries? Significant time was spent gaining a familiarity with the answers to these questions. To further this end a global survey was formulated and sent out to all of the ITU's 189 member countries to attempt to gain an intimate knowledge of the issues related to ICTs for developed and developing countries from each country's specific point of view. Appendix C discusses the result of this effort in further detail.

The second goal of setting up this developing world database was to set the stage for the feasibility study enacted in the thesis. It was desired to obtain, inter alia, an informed definition of the developing world and a key analysis to aid this formulation would be to see how GDP/Capita maps with the latitude and longitude of each country on a global sphere. Analysis such as this shared some insights as detailed further in Chapter 2. Table A.1 is an example of one of the many tables produced during the assemblage of the world database. This table in particular details only the countries in the defined +/ 30° developing world equatorial range and is ordered from 30° latitude south to 30° latitude north. An extended version of this key table which included the expanse of the world's countries for which data is available was vital in the production of Figure 2-4 which shows the results of mapping GDP/capita against latitude for 229 of the world's countries in 2002 US dollars. It was this analysis that led to the +/- 30° range being termed 'the developing world' for the purposes of this thesis.

Country	Lat (N+, S-)	Long (W-,E+)	Population	GDP/Capita
Chile	-30	-71	15,498,930	10,000
Lesotho	-29.5	28.5	2,207,954	2,450
South Africa	-29	24	43,647,658	9,400
Australia	-27	133	19,546,792	24,000
Swaziland	-26.5	31.5	1,123,605	4,200
Paraguay	-23	-58	5,884,491	4,600
Botswana	-22	24	1,591,232	7,800
Namibia	-22	17	1,820,916	4,500
New Caledonia	-21.5	165.5	207,858	15,000
Cook Islands	-21.23	-159.77	20,811	5,000
Reunion	-21.1	55.6	743,981	4,800
Mauritius	-20.28	57.55	1,200,206	10,800
Madagascar	-20	47	16,473,477	870
Tonga	-20	-175	106,137	2,200
Zimbabwe	-20	30	11,376,676	$2,450
Niue	-19.03	-169.87	2,134	3,600
Mozambique	-18.25	35	19,607,519	900
Fiji	-18	175	856,346	5,200
Bolivia	-17	-65	8,445,134	2,600
Vanuatu	-16	167	196,178	1,300
Saint Helena	-15.93	-5.7	7,317	2,500
French Polynesia	-15	-140	257,847	5,000
Zambia	-15	30	9,959,037	$870
American Samoa	-14.33	-170	68,688	8,000
Samoa	-13.58	-172.33	178,631	3,500
Malawi	-13.5	34	10,701,824	660
Wallis and Futuna	-13.3	-176.2	15,585	2,000
Mayotte	-12.83	45.17	170,879	600
Angola	-12.5	18.5	10,593,171	1,330
Comoros	-12.17	44.25	614,382	710

Country	Lat (N+, S-)	Long (W-,E+)	Population	GDP/Capita
Brazil	-10	-55	176,029,560	7,400
Peru	-10	-76	27,949,639	4,800
Tokelau	-9	-172	1,431	1,000
East Timor	-8.83	125.92	952,618	500
Solomon Islands	-8	159	494,786	1,700
Tuvalu	-8	178	11,146	1,100
Papua New Guinea	-6	147	5,172,033	2,400
Tanzania	-6	35	37,187,939	$610
Indonesia	-5	120	231,328,092	3,000
Seychelles	-4.58	55.67	80,098	7,600
Burundi	-3.5	30	6,373,002	600
Ecuador	-2	-77.5	13,447,494	3,000
Rwanda	-2	30	7,398,074	1,000
Congo, Republic of the	-1	15	2,958,448	900
Gabon	-1	11.75	1,233,353	5,500
Nauru	-0.53	166.92	12,329	5,000
Congo, Democratic Republic of the	0	25	55,225,478	590
Kenya	1	38	31,138,735	1,000
Sao Tome and Principe	1	7	170,372	1,200
Uganda	1	32	24,699,073	$1,200
Singapore	1.37	103.8	4,452,732	24,700
Kiribati	1.42	173	96,335	840
Equatorial Guinea	2	10	498,144	2,100
Malaysia	2.5	112.5	22,662,365	9,000
Maldives	3.25	73	320,165	3,870
Colombia	4	-72	41,008,227	6,300
French Guiana	4	-53	182,333	6,000
Suriname	4	-56	436,494	3,500
Brunei	4.5	114.67	350,898	18,000
Guyana	5	-59	698,209	3,600
Cameroon	6	12	16,184,748	1,700
Liberia	6.5	-9.5	3,288,198	1,100
Micronesia, Federated States of	6.92	158.25	135,869	2,000
Central African Republic	7	21	3,642,739	1,300
Sri Lanka	7	81	19,576,783	3,250
Palau	7.5	134.5	19,409	9,000
Cote d'Ivoire	8	-5	16,804,784	1,550
Ethiopia	8	38	67,673,031	700
Ghana	8	-2	20,244,154	1,980
Togo	8	1.17	5,285,501	$1,500
Venezuela	8	-66	24,287,670	$6,100

Country	Lat (N+, S-)	Long (W-,E+)	Population	GDP/Capita
Sierra Leone	8.5	-11.5	5,614,743	500
Marshall Islands	9	168	73,630	1,600
Panama	9	-80	2,882,329	5,900
Benin	9.5	2.25	6,787,625	1,040
Costa Rica	10	-84	3,834,934	8,500
Nigeria	10	8	129,934,911	840
Somalia	10	49	7,753,310	550
Guinea	11	-10	7,775,065	1,970
Trinidad and Tobago	11	-61	1,163,724	$9,000
Djibouti	11.5	43	472,810	1,400
Guinea-Bissau	12	-15	1,345,479	900
Grenada	12.12	-61.67	89,211	4,750
Netherlands Antilles	12.25	-68.75	214,258	11,400
Aruba	12.5	-69.97	70,441	28,000
Burkina Faso	13	-2	12,603,185	1,040
Cambodia	13	105	12,775,324	1,500
Nicaragua	13	-85	5,023,818	2,500
Philippines	13	122	84,525,639	4,000
Barbados	13.12	-59.53	276,607	14,500
Saint Vincent and the Grenadines	13.25	-61.2	116,394	2,900
Gambia, The	13.47	-16.57	1,455,842	1,770
Guam	13.47	144.78	160,796	21,000
El Salvador	13.83	-88.92	6,353,681	4,600
Saint Lucia	13.88	-61.4	160,145	4,400
Senegal	14	-14	10,589,571	1,580
Martinique	14.67	-61	422,277	11,000
Chad	15	19	8,997,237	1,030
Eritrea	15	39	4,465,651	740
Honduras	15	-86.5	6,560,608	2,600
Sudan	15	30	37,090,298	1,360
Thailand	15	100	62,354,402	$6,600
Yemen	15	48	18,701,257	$820
Northern Mariana Islands	15.2	145.75	77,311	12,500
Dominica	15.42	-61.33	70,158	3,700
Guatemala	15.5	-90.25	13,314,079	3,700
Cape Verde	16	-24	408,760	1,500
Niger	16	8	10,639,744	820
Vietnam	16	106	81,098,416	$2,100
Guadeloupe	16.25	-61.58	435,739	9,000
Montserrat	16.75	-62.2	8,437	2,400
Mali	17	-4	11,340,480	840
Antigua and Barbuda	17.05	-61.8	67,448	10,000
Belize	17.25	-88.75	262,999	3,250

Country	Lat (N+, S-)	Long (W-,E+)	Population	GDP/Capita
Saint Kitts and Nevis	17.33	-62.75	38,736	8,700
Laos	18	105	5,777,180	1,630
Anguilla	18.25	-63.17	12,446	8,600
Jamaica	18.25	-77.5	2,680,029	3,700
Puerto Rico	18.25	-66.5	3,957,988	11,200
Virgin Islands	18.33	-64.83	123,498	15,000
British Virgin Islands	18.5	-64.5	21,272	16,000
Dominican Republic	19	-70.67	8,721,594	5,800
Haiti	19	-72.42	7,063,722	1,700
Cayman Islands	19.5	-80.5	36,273	30,000
India	20	77	1,045,845,226	2,500
Mauritania	20	-12	2,828,858	1,800
Oman	21	57	2,713,462	8,200
Cuba	21.5	-80	11,224,321	2,300
Turks and Caicos Islands	21.75	-71.58	18,738	7,300
Burma	22	-98	42,238,224	1,500
Macau	22.17	113.55	461,833	17,600
Hong Kong	22.25	114.17	7,303,334	25,000
Mexico	23	-102	103,400,165	9,000
Taiwan	23.5	121	22,548,009	17,200
Bangladesh	24	90	133,376,684	1,750
United Arab Emirates	24	54	2,445,989	$21,100
Bahamas, The	24.25	-76	300,529	16,800
Libya	25	17	5,368,585	7,600
Saudi Arabia	25	45	23,513,330	10,600
Qatar	25.5	51.25	793,341	21,200
Bahrain	26	50.55	656,397	13,000
Egypt	27	30	70,712,345	3,700
Bhutan	27.5	90.5	2,094,176	1,200
Algeria	28	3	32,277,942	5,600
Nepal	28	84	25,873,917	1,400
Kuwait	29.5	45.75	2,111,561	15,100
Pakistan	30	70	147,663,429	2,100

Table A.1: Developing World Database

Appendix B

Detailed Description of Computer Model Modules

This Appendix B contains the technical details that comprise each of the modules in the satellite simulation employed in this analysis. It is taken directly from the appendix of the MIT Industry Systems Study on Communications Satellite Constellations produced by de Weck and Chang [deWDC03]. This systems study represents a comprehensive analysis of the simulation used in this thesis in the greater context of understanding how to perform a thorough study of the design space of complex engineering systems. The necessary changes that were made to the simulation to reflect the instantiation of the SMS based simulation used in this thesis are detailed below. There were also some aspects of de Weck and Chang's work which were not relevant for this analysis and were thus not included.

B.1 System Input File (SIF)

In the system input file (SIF), design variables, constants, and policy constraints are defined and bundled into their vector forms $\mathbf{x}$, $\mathbf{c}$, and $\mathbf{p}$.

There are two types of SIF. One of them represents a particular design. In this type of SIF each design variable has only a single value. The design vector is one-dimensional. Another kind of SIF represents a group of possible designs. In this type of SIF each design variable has an array of different values. Therefore the design vector is a two-dimensional array. Specified by hardware, policy constraints, and requirements, the parameters in $\mathbf{c}$, $\mathbf{p}$, and $\mathbf{r}$ always have just a single value in both types of SIF. An example for the first kind of SIF is the input file for any major established system, which contains exactly the values of parameters used within that of the Orbcomm system. The system input file makes the start file call all the simulation modules (once) in order to obtain the simulation results for Orbcomm. The second kind of SIF calls the modules multiple times until it finishes performing an exhaustive search of all allowable combinations of design variable values.

It should be noted that in the two-dimensional design vector array, design variables do not need to contain the same number of values. For example, orbital altitude can take five different values at 500km, 750km, 1,000km, 1,250km, and 1,500km, while minimum elevation angle has four values at 5°, 15°, 25°, and 35°. Figure B-1 demonstrates the difference between the two types of design vectors.

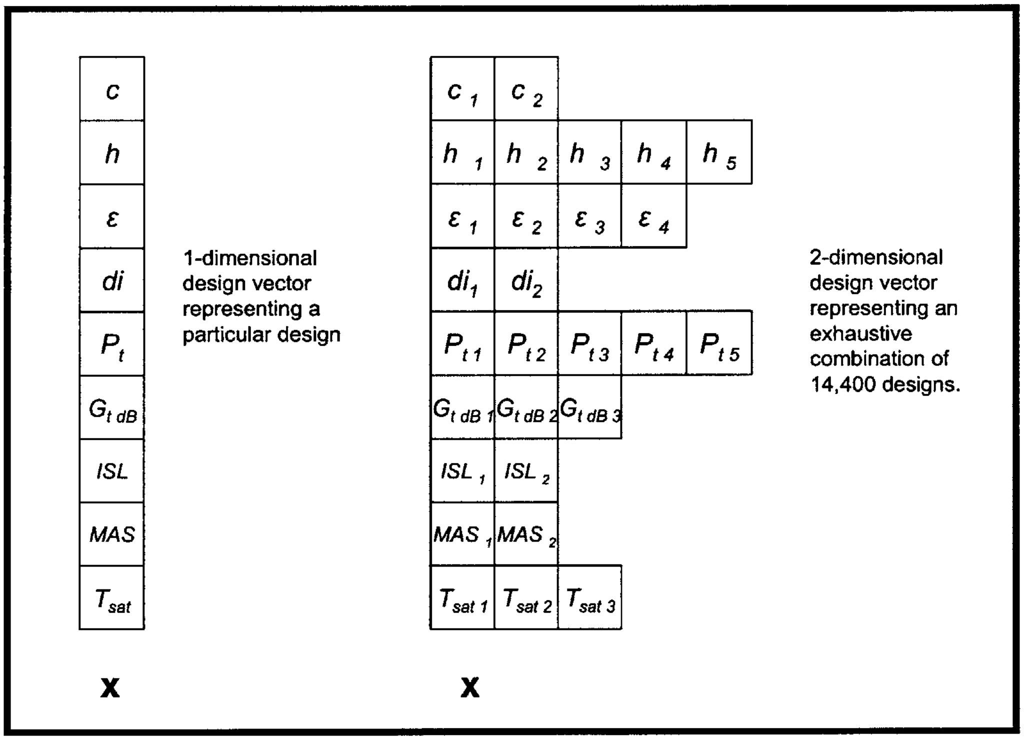


Figure B-1: One-dimensional design vector vs. Two-dimensional design vector.

The first case represents the simulation of a single architecture. The second case represents a combinatorial problem. SIF passes the bundled vectors to the start file.

B.2 Start File (SF)

After inputting design, constant, and policy vectors from the system input file, the start file first unbundles the vectors and assigns their values to local variables. It also keeps track of the size of each design variable. There is no need to track the size of the constants and policy constraints since they always have a size of 1.

After unbundling the design, constant, and policy vectors, SF first performs a number of checks on the input data. An example of such a check is to determine whether the antenna size required by the user-defined transmitter antenna gain (a design variable) is larger than 3 meters. This checking is done in sub-routine `LDRcheck.m`. If the size of the antenna is larger than 3 meters, `LDRcheck.m` will ask the user to enter lower value(s) for the transmitter gain, and returns the new value(s) as well as the variable dimensions to SF. The assumption here is that an antenna larger than 3 meters requires a large deployable reflector technology.

Using the design variable size information obtained when unbundling the design vector, SF runs an exhaustive combination of all selected values of design variables. This is a so called full-factorial run. In MATLAB, we achieve a full-factorial run through a set of nested for-loops. Each for-loop represents one design variable, iterating through all its allowable values. The one dimensional design vector example in Figure B-1 has nine for-loops, with a single iteration for each for-loop. Altogether this consists of one single run of the simulation. The two-dimensional design vector example used within the simulation also has nine for-loops, with, respectively, 1, 3, 3, 1, 2, 1, 2, 2, and 3 iterations for each for-loop. Altogether this leads to 216 simulation runs.

Individual simulations are almost entirely run inside the nested for-loops except for some post-processing. The SF, simply keeps track of the number of runs, makes calls to a series of subroutines and functions and directs the traffic of information among them. It also collects and post-processes outputs from the subroutines and functions that are of interests to the user.

Inside the nested for-loops, SF first stores the number of runs in a variable named result_count. It then calls the subroutine named requirements in which the requirements are calibrated based on the relation defined in Table 3.4. Then, SF makes calls to the following functions: coverage.m (CCM), satNetwork.m (SNM), spacecraft.m (SM), LV.m (LVM), either linkRate.m followed by MF-TDMA.m or linkEbNo.m followed by MF_CDMA.m depending on the type of multiple access scheme (CM), cost.m (TCM), and market.m (MM). After the execution of these functions, SF stores values of the objectives into vector **J** and values of the benchmarking metrics into vector **B**. After the nested for-loops end, post-processing procedures for finding the Pareto optimal solutions are carried out.

B.3 Coverage/Constellation Module (CCM)

CCM calculates the geometry and size of the constellation. The inputs into this module are the following: constellation type, orbital altitude, minimum elevation angle, diversity, satellite antenna spot beam gain, and the center frequency of the downlink bandwidth. The outputs of the module are the following: inclination angle, number of satellites in the optimal constellation design, number of orbital planes in the design, beamwidth of the edge cell spot beam, number of cells, the distance from a satellite to the center of its edge cells, orbital period, duration of a beam over a center cell, satellite antenna dimension, and footprint area.

CCM starts with the calculation of some basic constellation geometric parameters including the satellite nadir angle ϑ and the corresponding central angle ψ as in the following equations, where R_e stands for the Earth radius, r for orbital altitude measured from the center of earth, and ε for minimum elevation angle.

$$\vartheta = \arcsin\left(\frac{R_e}{r}\cos\varepsilon\right) \qquad \text{(B.1)}$$

$$\psi = \arccos\left(\frac{R_e}{r}\cos\varepsilon\right) - \varepsilon \qquad (B.2)$$

The simulation is equipped to deal with both Polar and Walker systems. To calculate the geometry of polar or Walker constellations, depending on which type of constellation the design uses, CCM calls polar.m or walker_lang.m. However for the analysis in this thesis only Walker systems are used and thus polar.m is never run.

When walker_lang.m is called, the file employs a numerical optimization of Walker constellation designs developed by Lang and Adams.[TLWA97] The optimization is not a simple function where we can plug in orbital altitude and minimum elevation and output *N*/*P*/*F* (This is a classic way of representing the geometry of a Walker constellation, where *N* is the same as N_{sat}, *P* is the number of planes, and *F* is the phasing factor that determines the angular offset between the satellites in adjacent orbit planes). Numerical optimization of *P*/*F* needs to be performed and inclination for each value of N_{sat} needs to be deciphered. By optimization we mean the configuration that requires the smallest value of ψ to achieve continuous global coverage. This will be the constellation that can be operated at the lowest altitude and still give global coverage. Conversely, at the same altitude it will offer the largest values of minimum elevation angle and still achieve coverage. The result is a table which contains optimized Walker constellations of from 5 to 197 satellites for continuous one fold coverage of the 30° S to 30° N latitude zone. The details of this table are shown in Table B.1.

Values of N/P/F which as stated earlier are the Walker parameters of the optimal constellation are outputted in Table B.1 along with I, the optimal inclination (where 0.4 is approximately equal to an inclination of 0 degrees), and thmax, which is the size of the coverage circle (measured in earth central angle of the radius, ψ) required to obtain the desired coverage. This value of coverage circle angle, theta, can be obtained from knowledge of the constellation altitude and minimum usable elevation angle. The table also outputs a value, Latmx, which is the latitude at which a hole will open if the coverage circle is too small. NGT stands for number of (independent) ground tracks and indicates a suspicious solution if it is too small (none present in Table B.1). Note that it can be seen that the number of satellites parameter does not run continuously from 5 to 197 satellites as some constellations were inefficient; that is there existed a smaller constellation providing the same coverage requiring the same or smaller theta. Also when the constellation is an equatorial one (i.e., inclination=0 degrees, actually 0.4 in the Table B.1), it actually means a symmetric distribution of satellites about the equator.

N	P	F	I	THMAX	LATMX	NGT
5	5	1	0.400	45.609	30.00	5
6	2	0	0.400	41.561	30.00	6
7	7	1	0.400	38.785	30.00	7
8	4	1	0.400	36.988	30.00	8
9	9	6	0.400	35.703	30.00	9
10	10	2	0.400	34.658	30.00	10
11	11	6	0.400	33.953	30.00	11
12	2	1	0.400	33.320	30.00	12
13	13	1	0.400	32.813	30.00	13
14	14	10	0.400	32.483	30.00	14
15	15	12	27.400	31.638	30.00	15
16	16	6	27.500	30.070	30.00	16
17	17	4	26.100	29.484	17.50	17
18	9	5	25.800	28.189	30.00	18
19	19	11	26.200	27.153	1.00	19
20	5	4	25.600	26.648	14.50	20
21	7	2	25.000	25.974	1.00	21
22	22	4	25.300	25.179	30.00	22
23	23	17	25.700	24.651	13.00	23
24	12	3	24.400	24.336	0.00	24
25	5	3	24.700	23.820	30.00	25
26	13	6	25.300	23.362	30.00	26
27	27	9	23.600	23.178	30.00	27
28	28	2	23.700	22.632	11.50	28
29	29	7	25.100	22.320	30.00	29
30	15	10	24.700	21.595	30.00	10
32	32	8	24.300	21.549	18.50	32
33	33	20	24.700	20.678	30.00	11
35	35	12	24.300	20.249	30.00	35
36	12	6	24.500	19.765	6.00	12
37	37	22	24.400	19.586	16.00	37
38	19	12	24.800	19.381	30.00	38
39	13	1	23.700	19.065	30.00	39
40	40	30	23.700	18.870	30.00	40
41	41	8	24.200	18.524	0.00	41
42	14	6	24.600	18.478	0.50	42
43	43	29	23.000	18.392	1.50	43
44	22	11	23.300	18.102	30.00	44
45	9	8	23.600	17.922	0.00	45
46	46	26	24.700	17.873	30.00	46
47	47	40	25.700	17.547	20.50	47
48	6	3	25.800	17.449	30.00	48
49	49	5	26.500	17.195	4.00	49

50	50	10	25.100	16.980	30.00	50
51	17	8	24.900	16.744	30.00	51
52	52	22	25.000	16.583	5.50	52
53	53	46	25.200	16.506	5.00	53
54	6	2	25.700	16.307	4.00	54
55	11	0	24.400	16.152	30.00	55
56	28	9	24.400	15.997	6.00	56
57	57	16	24.300	15.929	30.00	57
58	29	21	24.700	15.801	5.00	58
59	59	15	23.900	15.635	30.00	59
60	60	48	23.900	15.582	6.50	60
61	61	10	23.900	15.439	30.00	61
62	62	54	26.800	15.304	1.00	62
63	7	4	26.600	15.094	1.50	63
64	64	6	26.700	15.020	9.50	64
65	65	35	26.800	14.805	9.00	65
66	22	4	26.900	14.786	30.00	66
67	67	19	25.900	14.679	30.00	67
68	34	25	25.800	14.542	1.00	68
69	69	61	25.800	14.312	30.00	69
70	7	3	26.000	14.291	2.00	70
71	71	6	26.200	14.143	30.00	71
73	73	52	25.100	14.049	0.50	73
74	74	46	25.200	13.866	1.00	74
75	75	33	25.300	13.788	30.00	75
76	76	68	25.400	13.694	30.00	76
77	7	2	25.800	13.624	2.50	77
78	78	6	26.100	13.547	2.50	78
80	20	9	24.700	13.473	1.00	80
81	27	17	24.800	13.358	30.00	81
82	41	32	25.000	13.279	1.50	82
83	83	57	26.800	13.197	30.00	83
84	42	23	27.100	13.168	1.50	84
85	17	3	27.200	13.097	30.00	85
86	86	38	26.600	13.060	30.00	86
87	87	78	26.400	12.912	3.50	87
88	8	4	26.300	12.783	30.00	88
89	89	7	26.400	12.697	30.00	89
90	90	48	26.300	12.632	30.00	90
91	91	32	26.500	12.596	30.00	91
93	31	20	25.900	12.524	30.00	93
94	47	37	25.800	12.427	30.00	94
95	95	86	26.000	12.282	3.50	95
96	8	3	25.800	12.203	30.00	96
98	49	37	28.100	12.189	4.50	98
99	33	5	26.300	12.187	1.50	99
100	25	4	26.600	12.077	1.00	100
101	101	30	25.400	11.957	3.50	101
102	102	46	25.500	11.864	30.00	102
103	103	27	27.200	11.812	3.00	103
104	104	84	27.300	11.763	3.50	104
105	105	18	27.500	11.724	3.50	105
107	107	67	27.800	11.660	4.50	107
108	9	5	26.800	11.618	30.00	108
109	109	69	25.200	11.566	3.50	109
110	55	7	26.600	11.505	2.50	110
111	37	6	26.700	11.332	30.00	111

113	113	46	26.900	11.309	30.00	113
114	19	3	27.000	11.294	30.00	114
115	115	52	26.400	11.293	30.00	115
117	117	84	28.000	11.175	0.50	117
118	118	8	26.200	11.080	30.00	118
119	119	63	26.100	11.075	2.50	119
120	120	82	26.300	11.023	30.00	120
121	121	92	26.400	10.968	3.00	121
123	123	78	25.900	10.901	1.50	123
125	125	51	27.500	10.771	1.00	125
126	21	4	27.500	10.748	7.00	126
128	32	17	27.400	10.666	0.00	128
129	43	29	27.600	10.641	0.00	129
131	131	119	27.900	10.614	30.00	131
132	132	70	27.000	10.564	2.00	132
133	133	91	27.000	10.433	1.50	133
134	134	102	27.000	10.344	6.50	134
137	137	20	27.000	10.321	0.50	137
138	138	52	27.200	10.278	30.00	138
139	139	31	27.400	10.258	30.00	139
140	10	5	26.700	10.190	2.50	140
142	71	8	26.500	10.093	6.00	142
144	72	39	26.600	10.051	1.00	144
146	73	50	26.600	10.026	0.50	146
147	21	3	26.900	10.002	0.50	147
149	149	116	27.200	9.954	0.00	149
150	10	4	26.200	9.901	6.00	150
152	152	80	26.100	9.839	1.50	152
153	51	7	26.200	9.831	6.50	153
157	157	135	26.700	9.725	7.50	157
159	159	33	27.100	9.620	2.50	159
161	23	4	27.100	9.592	3.00	161
163	163	127	27.100	9.574	3.50	163
164	82	33	27.200	9.556	4.00	164
165	11	6	27.100	9.551	1.50	165
166	166	38	25.700	9.523	5.00	166
167	167	88	26.700	9.478	2.00	167
168	56	8	26.600	9.401	30.00	168
170	34	6	26.700	9.305	3.00	170
172	172	148	26.900	9.282	3.00	172
176	11	5	26.500	9.233	2.00	176
178	89	9	26.400	9.128	30.00	178
181	181	146	26.500	9.051	3.00	181
183	183	79	26.700	8.992	3.50	183
186	186	174	26.400	8.905	1.50	186
189	189	99	26.200	8.888	30.00	189
190	38	20	27.300	8.803	6.50	190
193	193	89	27.500	8.794	7.50	193
194	194	56	26.600	8.782	3.50	194
196	14	13	27.800	8.778	30.00	196
197	197	185	25.900	8.734	2.00	197

Table B.1: Lang's optimized Walker constellations for continuous one fold coverage of the 30° S to 30° N latitude zone. [TLWA97]

Hence this resulting Table B.1 contains the best P/F and inclination values for each N_{sat}, along with the minimum value of ψ to achieve the designated equatorial coverage. All constellations produced in Table B.1 have a diversity of 1. The file `walker_lang.m` goes through the following steps to find an optimal Walker constellation:

1. Compute central angle ψ using equation (2).
2. Scan down the table to the first entry (lowest number of satellites) for which the table value of ψ (required) is less than the value in step1 (available). This is the optimal constellation for the design. The $N/P/F$ and inclination are given in the table. Read the value of N from the table.

At the end, `walker_lang.m` returns the value of optimal $N/P/F$ and inclination I to `coverage.m`. The geometry of a satellite in a Walker constellation providing global coverage is shown in Figure B-2. Note that the analysis in this research only requires a Walker constellation to provide coverage between the 30° N to 30° S equatorial belts so the coverage area would be limited to this zonal region and hence would not be as extensive as shown in Figure B-2.

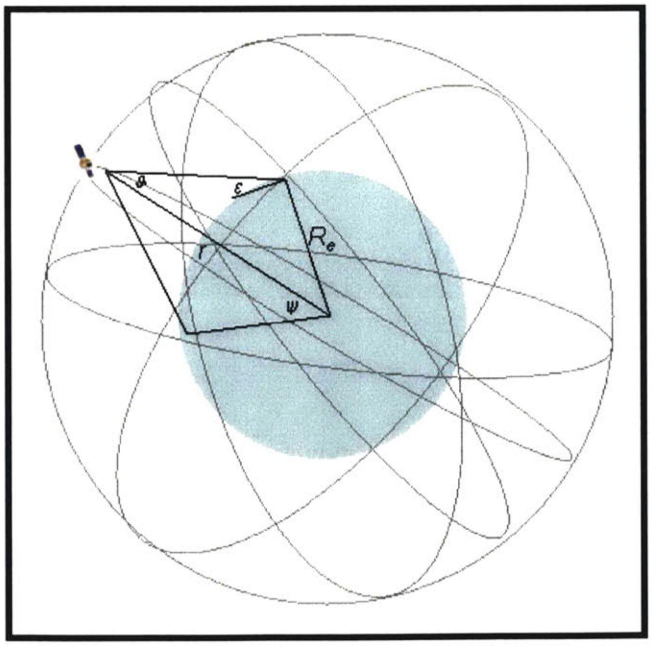


Figure B-2: Geometry of a satellite in a Walker Constellation providing global coverage

After calculating the formation of the constellation, the module finds the dimension of satellite transmitter. First, the wavelength λ of the transmission is the ratio between the speed of light c and the average frequency of the downlink bandwidth f

$$\lambda = c/f \tag{B.3}$$

Then, using $G_{t\ edge}$ the edge cell gain converted from $G_{t\ dB}$, the dimension of satellite transmitter is

$$D_{sat\ trans} = \lambda\sqrt{G_{t\ edge}}\Big/\pi \tag{B.4}$$

Another calculation is dedicated to finding the number of cells in the footprint of a satellite. First, the beamwidth θ_{edge} of an edge cell is found to be

$$\theta_{edge} = \frac{35\pi}{\sqrt{G_{t\ edge}}} \tag{B.5}$$

And footprint area and slant range are respectively found to be

$$A_{foot} = 2\pi R_e^{\ 2}(1-\cos\psi) \tag{B.6}$$

and

$$R_{slant} = \sqrt{R_e^{\ 2} + r^2 - 2R_e r\cos\psi} \tag{B.7}$$

Figure B-3 helps in understanding the following geometric derivation. Essentially, we will try to find the hexagonal areas of the edge cell and center cell. Then we divide the footprint area with the average of the two hexagonal areas to estimate the total number of cells in the footprint. Let,

$$\alpha_1 = \vartheta - 2\theta_{edge} \qquad \text{(B.8)}$$

where β_1 is the earth centered angle corresponding to α_1.

$$\beta_1 = \arcsin\left(\frac{r}{R_e}\sin\alpha_1\right) - \alpha_1 \qquad \text{(B.9)}$$

$$\gamma_1 = \psi - \beta_1 \qquad \text{(B.10)}$$

The radius of the edge cell is

$$r_{edgecell} = 1/2\, R_e \gamma_1 \qquad \text{(B.11)}$$

The circular area of the edge cell is

$$A_{edgecell} = 2\pi R_e^{\,2}\left(1 - \cos(\gamma_1/2)\right) \qquad \text{(B.12)}$$

And the hexagonal area is

$$A_{edgehexa} = \frac{3}{\pi}\sin\left(\frac{\pi}{3}\right) A_{edgecell} \qquad \text{(B.13)}$$

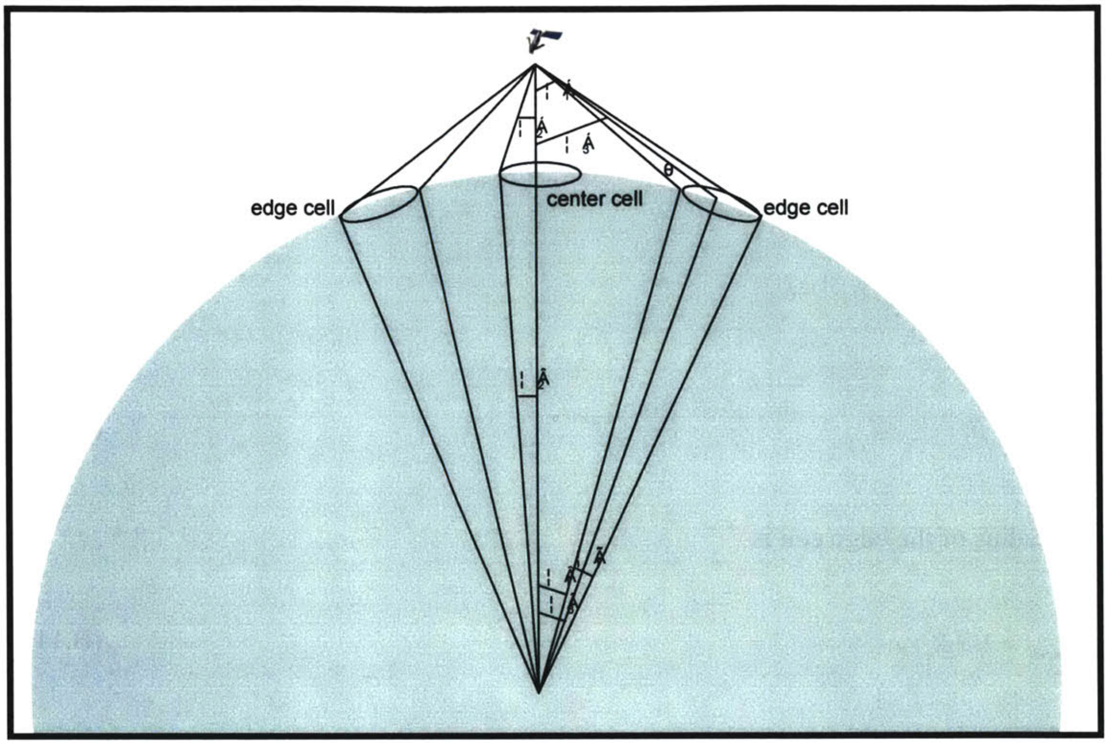


Figure B-3: Geometry involved in calculating single satellite coverage

Because the distance from the edge cell to the satellite is larger than the distance from the center cell to the satellite, to keep the same cell area the edge cell beam width needs to be narrower than the center cell beam width. In other words, the gain of the edge cell spot beam needs to be larger than the gain of the center cell spot beam. Iridium's edge cell gain is 6dB larger than the gain of the center cell. We can assume this to be the general case and get

$$G_{t\ center\ dB} = G_{t\ dB} - 6 \tag{B.14}$$

The beamwidth of the center cell spot beam is

$$\theta_{center} = \frac{35\pi}{\sqrt{G_{t\ center}}} \tag{B.15}$$

Let

$$\alpha_2 = \theta_{center} \tag{B.16}$$

$$\beta_2 = \arcsin\left(\frac{r}{R_e}\sin\alpha_2\right) - \alpha_2 \tag{B.17}$$

The radius of the center cell is

$$r_{centercell} = 1/2\, R_e \beta_2 \tag{B.18}$$

The circular area of the center cell is

$$A_{centercell} = 2\pi R_e^{\,2}\left(1 - \cos(\beta_2/2)\right) \tag{B.19}$$

And the corresponding hexagonal area is

$$A_{centerhexa} = \frac{3}{\pi}\sin\left(\frac{\pi}{3}\right) A_{centercell} \tag{B.20}$$

Then, the number of cells per footprint is estimated to be

$$N_{cell} = 2\,\mathrm{round}\left(\frac{A_{foot}}{\left(A_{centerhexa} + A_{edgehexa}\right)/2}\right) \tag{B.21}$$

The factor of 2 compensates for the overlapping of cells in the footprint.

Besides the number of cells per footprint, this module also takes care of the calculation of the distance from satellites to the center of an edge cell, the orbital period, and the duration of a beam over a center cell for use in later modules.

To find the distance from a satellite to the center of an edge cell, let

$$\alpha_3 = \vartheta - \theta_{edge} \tag{B.22}$$

where β_3 is the earth centered angle corresponding to α_3

$$\beta_3 = \arcsin\left(\frac{r}{R_e}\sin\alpha_3\right) - \alpha_3 \tag{B.23}$$

The distance is then

$$D_{edge} = \sqrt{R_e^{\,2} + r^2 - 2R_e r\cos\beta_3} \tag{B.24}$$

To find the orbital period in minutes,

$$T_{orbit} = \frac{1}{60}\left(2\pi\sqrt{r^3/GM_{earth}}\right) \tag{B.25}$$

where GM_{earth} is the Earth's gravitational constant (=398601km^{3}sec^{-2}).

To find the duration of a beam over a center cell, the orbital angular velocity of satellite in (rad/s) is

$$\omega_{cir} = 631.34812r^{-3/2} \tag{B.26}$$

The central angle of a center cell is 2 β_2. Then, the cell duration T_{cell} is

$$T_{cell} = 2\beta_2/\omega_{cir} \tag{B.27}$$

Upon finishing all the calculations, CCM passes the values of the outputs back to SF. SF calls the next module, which is the satellite network module.

B.4 Satellite Network Module (SNM)

SNM does some calculation that scales the network. The inputs of the module include constellation type, the Boolean variable representing the availability of ISL, number of satellites, number of orbital planes, and the footprint area. It can be seen that the last three inputs are outputs from CCM. The outputs of SNM include gateway thousand lines of code, number of gateways, and number of personnel staffed at the gateways.

Gateway thousand lines of code is an important parameter useful for estimating system life-cycle cost. In this study it is estimated to be 6.3 thousand lines per gateway for LEO systems. This estimation is based on the FCC filings of four systems including ARIES, Globalstar, ORBCOMM, and Starnet.

In estimating the number of gateways, distinctions are made between systems with ISL and systems without ISL. Two assumptions were made. The first assumption is that for systems with ISL, the number of gateways can be made to scale with the number of gateways present in the Orbcomm system. For the total number of satellites in the Orbcomm system which was 36 satellites, there were 9 gateways utilized. Thus for the system in this research the number of gateways required was made to be proportional to the number of satellites used in the system (given by N_{sat} in equation B.28 below). Hence the number of gateways for a non ISL system was implemented in this module as:

$$N_{GW} = \text{round}\left(9_{GW} \times \frac{N_{sat}}{36_{satellites}} \right) \qquad \text{(B.28)}$$

For systems with ISL, the assumption was made that two gateways are needed per orbital plane. Although in theory an ISL system needs just one gateway to interface the space segment with the ground segment, in practice each orbital plane should have two gateways to diverge the communication traffic. Indeed this is the design adopted by Iridium. Therefore the number of gateways for an ISL system is simply

$$N_{GW} = 2P \tag{B.29}$$

where P is the number of planes.

The number of personnel is estimated assuming at any moment there are three personnel members stationed at each gateway on a eight-hour rotating schedule. So the total number of personnel at all gateways are

$$N_{personnel} = N_{GW} \times 3 \times \left(\frac{24\text{hrs.}}{8\text{hrs.}} \right) \tag{B.30}$$

After the above calculations, SNM passes the output values back to SF.

B.5 Spacecraft Module (SM)

The next module called by SF is SM. The inputs of this module are satellite transmitter power, ISL, thousand lines of code of gateway, apogee kick motor specific impulse, station keeping engine specific impulse, orbital altitude, space life of the system, ISL datarate, and satellite transmitter antenna dimension. The outputs of the module are satellite mass, injection fuel mass, antenna weight, communication electronics weight, spacecraft bus dry weight, beginning of life power, apogee kick motor type, apogee kick motor dry weight, apogee kick motor impulse, and flight software thousand lines of code.

Although SM has multiple outputs, its major product is the satellite in-orbit wet mass. This mass is important to launch vehicle selection and cost estimation in later modules. To estimate this mass, a combination of analogy with existing system, scaling from existing systems, and budgeting by components is used. SM first estimates the relationship between the dry mass of spacecraft without ISL and its payload power based on data from the FCC filings of twenty-three LEO personal communication systems collected by Phil Springmann in November 2002. [PSdeW04]

$$M_{dry} = 11.025 P_t^{0.6076} \tag{B.31}$$

The data are shown in Figure B-4.

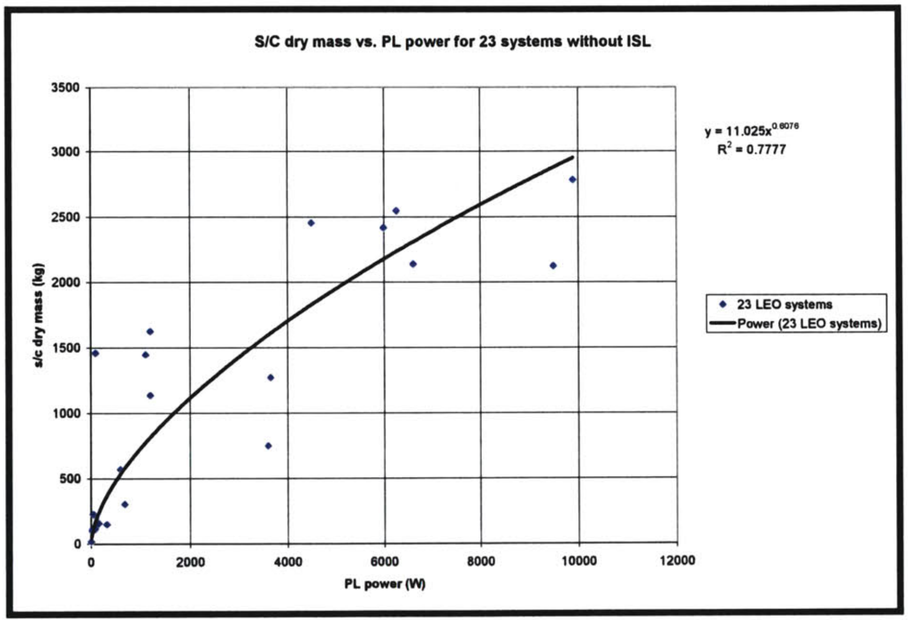


Figure B-4: Relationship between dry mass of spacecraft without ISL and payload power based on the FCC filings of 23 LEO personal communication systems.

After the spacecraft dry mass, the antenna weight is estimated from the transmitter antenna dimension. The relationship between antenna weight and antenna size is estimated based on data provided in Larson and Wertz [WLJR99] as what follows

$$M_{ant} = 9.1734 D_{sat\ trans}^{1.4029} \tag{B.32}$$

The data are shown in Figure B-5.

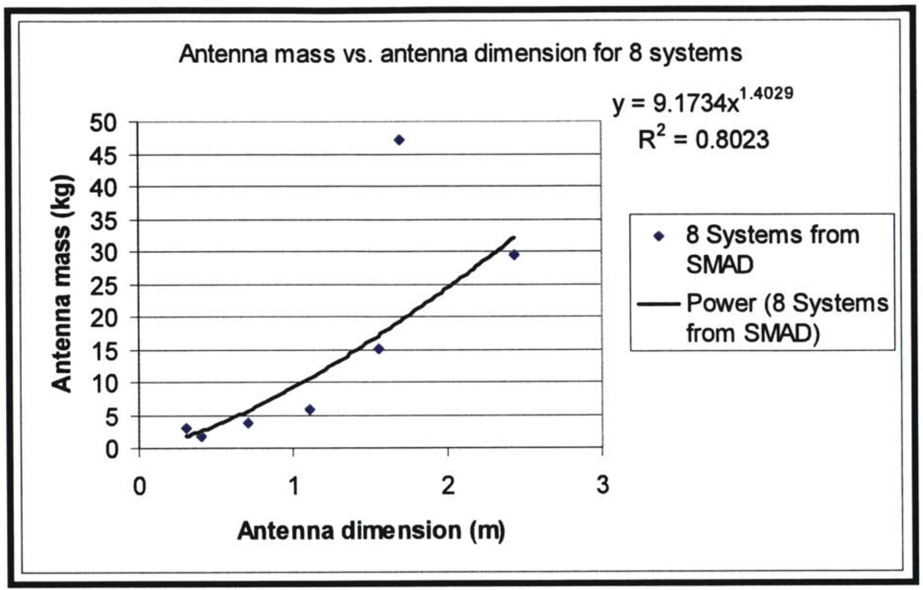


Figure B-5: Relationship between antenna mass and antenna dimension based on the data of 8 systems provided in Larson and Wertz [WLJR99]. Note that the reference [WLJR99] is referred to as 'SMAD' in the legend of the Figure.

If the mass of the receiver antenna is assumed to be same as the transmitter, then a factor of 2 is added to represent both antennas.

An estimation of the ISL weight is made based on information provided by Yoshisada Koyama at Next-Generation LEO System Research Center (NeLS) in Japan. The assumption is that the ISL system of a satellite has four links. The mass is estimated to be 426 kg for a radio frequency (RF) ISL with data rate lower than 100 Mbps, 480 kg for an RF ISL with data rate higher than 100 Mbps, and 117 kg for an optical ISL (OISL) with data rate of 10 Gbps.

Using the dry mass of spacecraft without ISL and ISL (if applicable) as initial value, M_{sat} goes through an iteration in which the significant portions of the spacecraft fuel mass are added. An iteration is used because the deorbiting and station-keeping fuels added at later steps of the calculation will affect the spacecraft cross-section area calculated in earlier steps. It has been shown that M_{sat} typically converges to within 0.01% of its value in less than 10 iterations. The structure of the iteration is shown below in Figure B-6.

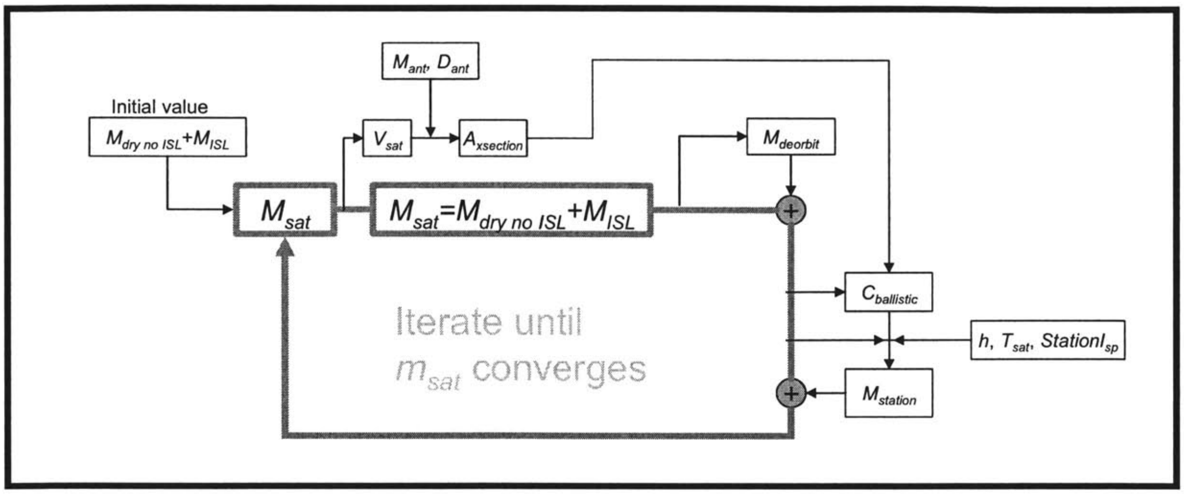


Figure B-6: Iterations to find satellite mass.

As shown in Figure 3-6, the first step in the iteration is to find the volume and cross-sectional area of the satellite. This step is done in a subroutine named scgeometry.m. Based on data from fifteen LEO communication systems collected by Phil Springmann in November 2002, the average density of this type of spacecraft is found to be 234.18 kg/m^3. Since the volume will later be used in finding the satellite storage capacity of rocket fairings, we include the entire mass of the satellite, including the antenna, to find the volume

$$V_{sat} = \frac{M_{sat}}{234.18\,{}^{\mathrm{kg}}\!/\!_{\mathrm{m}^3}} \tag{B.33}$$

Next, we find the cross-sectional area of the satellite in orbit. Since in orbit the antennas are often unfolded from the spacecraft, we will account antenna area separately from spacecraft cross-section area. Assuming spherical shape of spacecraft and circular shape of antennas, the total cross-section area of the spacecraft and antennas is

$$A_{x\,\mathrm{section}} = \pi\left(\frac{3}{4\pi}\frac{M_{sat} - M_{ant}}{234.18\,{}^{\mathrm{kg}}\!/\!_{\mathrm{m}^3}}\right)^{\frac{2}{3}} + 2\pi\left(\frac{D_{sat\ trans}}{2}\right)^2 \tag{B.34}$$

Again, a factor of 2 is added to represent both the transmitter and receiver.

The third step is to add deorbiting fuel mass to satellite mass. The deorbiting fuel mass is found in subroutine `deorbit.m`. First the delta V for deorbiting is suggested by the following equation [WJLR99]

$$\Delta V_{deorbit} \approx V\left(1-\sqrt{\frac{2R_E}{R_E+r}}\right) \tag{B.35}$$

where R_E is earth radius and r earth-centered orbital radius.

This equation assumes the deorbiting process brings the satellite from its original orbital altitude to the earth's surface. But the FCC filings of both Iridium and Globalstar suggest that a ΔV much smaller than defined by Equation (B.35) is needed. In practice, the decommissioned satellite is propelled only to an altitude low enough to avoid collision with the other satellites in the constellation, and the rest of the descending is natural decay due to friction. In the simulation, de Weck and Chang assume the satellite is thrust to 90% of its original orbital altitude. So Equation (B.35) becomes

$$\Delta V_{deorbit} \approx V\left(1-\sqrt{\frac{2(R_E+0.9h)}{(R_E+0.9h)+r}}\right) \tag{B.36}$$

To find the fuel needed for deorbiting, we first find the sum of fuel and satellite using equation

$$M_{fuel+sat} = M_{sat}e^{\Delta V_{deorbit}/gI_{sp\ station}} \tag{B.37}$$

The specific impulse of station-keeping thruster is used because the same thruster is assumed to be used for decommission, which is very often the case. Then the fuel mass is found simply by

$$M_{fuel} = M_{fuel+sat} - M_{sat} \tag{B.38}$$

The value of deorbiting fuel mass is returned to spacecraft.m and added to total satellite mass.

The next step is to find station-keeping fuel mass. For satellites with circular orbit at low altitude, the most significant disturbance comes from atmosphere drag. The other disturbances due to earth's oblateness and third-body interaction are negligibly small compared with drag. The first thing to be found is ballistic coefficient $C_{ballistic}$. In ballistic.m, the cross-sectional area calculated earlier is used. According to Larson and Wertz [WLJR99], an approximate value of 2.2 should be used for drag coefficient C_d. Then ballistic coefficient $C_{ballistic}$ is

$$C_{ballistic} = \frac{M_{sat}}{C_d A_{x\,section}} \tag{B.39}$$

After ballistic.m, station.m is called. In station.m, the density at the particular orbital altitude is interpolated through atmosphere density data that are available in many references. Then the mean ΔV per year required to maintain altitude (in m/s per year) is

$$\Delta V_{station} = \frac{\pi \rho r V}{C_{ballistic} T_{orbit}} \tag{B.40}$$

where r is orbital radius in meter, V orbital velocity in *m/s*, $C_{ballistic}$ ballistic coefficient in kg/m^2, and T_{orbit} orbital period in year. This equation can be found in column 6 on the back sheet of the text by Larson and Wertz. [WLJR99]

After knowing the ΔV required for station-keeping, the station-keeping fuel mass is calculated using Equation (B.37) and (B.38) as described above. This mass is added to satellite mass.

The calculation of station-keeping fuel mass concludes the iteration. The iteration loops until the mass of satellite converges. Although the satellite includes orbital injection fuel at launch, but this part of the fuel has been used up when the satellite enters the orbit, and therefore does not affect the iterative calculation of satellite mass when the satellite is in orbit.

It should be noted that the order of calculations on different masses is designed to be the reverse of their order of removal from the satellite during its life. The dry mass and ISL mass (if applicable) are the original masses of the satellite. Deorbiting fuel stays on satellite throughout satellite's lifetime and is used only at the end of it, therefore its mass is the next to be calculated and added to total satellite mass. The station-keeping fuel is consumed throughout the lifetime of the satellite, and its mass is the last to be calculated and added to satellite mass. The orbit injection fuel is used up before the satellite enters the orbit, therefore its mass is not included in the iterative calculation. Indeed, it is the first thing to be calculated outside the iteration.

The calculation of orbital injection fuel depends not only on characteristics of the spacecraft and orbit, but also on the launch vehicle employed to send the spacecraft to the orbit from where the injection will happen. Different launch vehicles vary from each other in flight profile. Even the same launch vehicle has different versions that are customized to be mission-specific. It is difficult to make a generic calculation for the injection fuel requirement for a specific design. de Weck and Chang were only able to make a rough estimation based on available data of existing systems. In its FCC filing, the original design of Iridium uses 17.5 kg of fuel to inject 323.2 kg of in-orbit wet mass. The original design of Globalstar uses 30 kg of fuel to inject 232.0 kg of in-orbit wet mass. The average of the two systems is 23.75 kg of injection fuel for 277.6 kg in-orbit wet mass. A reasonable assumption is that the injection fuel mass is linearly proportional to in-orbit wet mass. So the following relation for a ballpark estimation of injection fuel mass is derived

$$M_{insertion} \approx 23.75 \times \frac{M_{sat}}{277.6} \qquad \text{(B.41)}$$

Together with a few other inputs, $M_{insertion}$ is plugged into insertion.m. In insertion.m, we find the impulse and dry weight of the apogee kick motor (AKM) that propels the orbit injection. These two quantities will be useful in finding the life-cycle cost of the system. First, the $\Delta V_{insertion}$ for orbital insertion is found using an equation from Larson and Wertz [WLJ99]

$$\Delta V_{insertion} = gI_{sp\ insertion} \ln \frac{M_{sat} + M_{insertion}}{M_{sat}} \tag{B.42}$$

Then the impulse for the AKM in kg·m/s is

$$J_{AKM} = M_{sat} \Delta V_{insertion} \tag{B.43}$$

But the cost model that will be used later requires J_{AKM} in kg·s, so we use a modified equation

$$\hat{J}_{AKM} = M_{sat} \Delta V_{insertion} / g \tag{B.44}$$

Since AKM is typically a solid-fuel motor, its dry weight can be estimated using data on solid rocket motors provided in in Larson and Wertz [WLJR99]. Based on 12 existing motors, a relation can be found between the dry weight and the total impulse of the motor, as illustrated in Figure B-7.

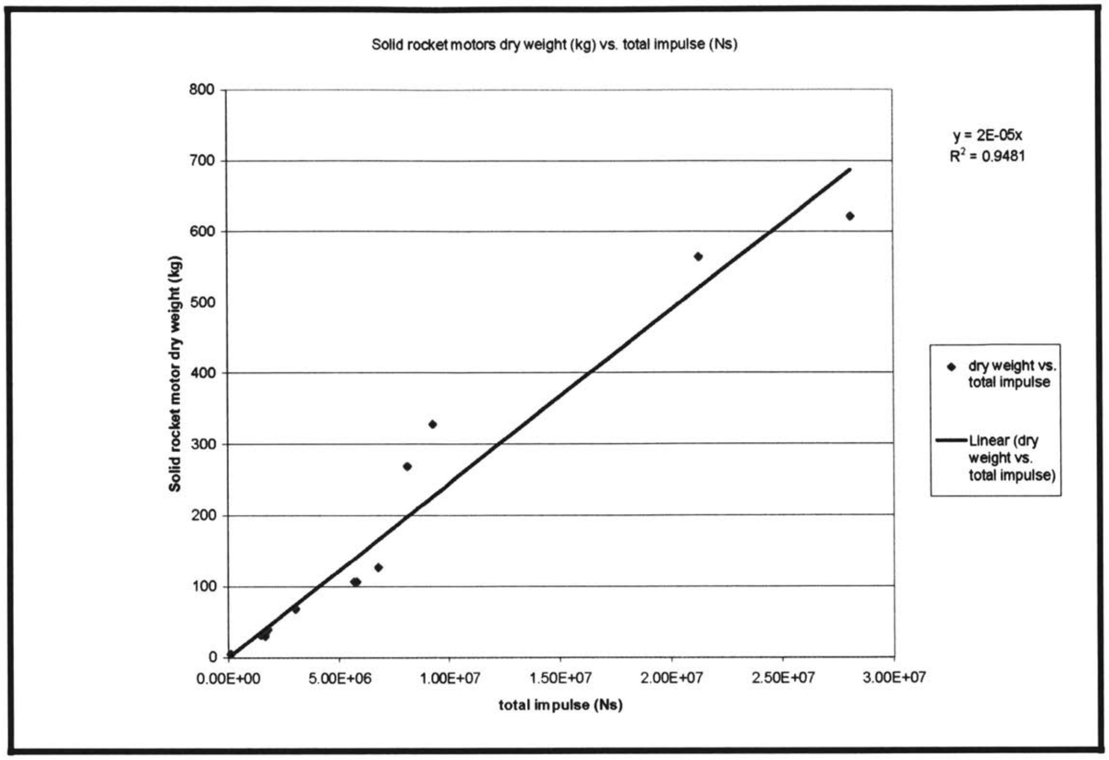


Figure B-7: Solid motor dry weight vs. total impulse.

In mathematical form, the relation is

$$AKMDW = 2 \times 10^{-5} J_{AKM} \tag{B.45}$$

The quantities calculated in insertion.m are returned to spacecraft.m.

A few more parameters are prepared for use in estimating the system life-cycle cost. These parameters are communication electronics weight (*CEW*), spacecraft bus dry weight (*SCBDW*), beginning of life power (*BLP*), and flight software thousand lines of code (*FSKLOC*). Based on data from existing systems, basic scaling relations are found to be

$$CEW = 0.27 M_{sat} \tag{B.46}$$

$$SCBDW = 0.436M_{sat} \tag{B.47}$$

$$BLP = 2.61P_t \tag{B.48}$$

FSKLOC is approximated equal to gateway thousand lines of code that has been calculated in satNetwork.m.

This concludes all the calculations in spacecraft.m. The module returns all useful values to the start file (SF).

B.6 Launch Vehicle Module (LVM)

The LVM checks six launch vehicles against the satellite mass and volume and selects the ones that are capable of launching the satellites to the designed orbit. Among the capable launch vehicles, the module then selects the one with lowest launch cost. The inputs of the module are satellite mass (including insertion fuel mass), orbital inclination angle, orbital altitude, and number of satellites in the constellation. The outputs that are of interests to this research are the name of the selected launch vehicle, number of satellites per vehicle, number of launches, selected launch site, launch success ratio of the selected launch vehicle, launch cost, and counter of capable vehicles.

The six launch vehicles are: Atlas IIIA (U.S.A.), Delta II 7920 (U.S.A.), H-IIA 202 (Japan), Long March 2C (China), Pegasus XL (U.S.A.), and Ariane 5 (Europe). Except Long March 2C and Ariane 5, the launch capability data are from International Reference Guide to Space Launch Systems published by AIAA. [SIJHJH99] The data on Long March 2C and Ariane 5 are from the official website of their service providers, respectively. [CALT03], [ARSE03]

The launch capability data of a vehicle are typically given in diagram as shown in Figure B-8. The diagram is specifically for launching into circular orbits. The x-axis stands for orbital altitude and the y-axis stands for payload mass that the vehicle is capable to send up. Each curve represents a different orbital inclination angle. The highest curve is the lower bound of orbital inclination the launch vehicle is able to reach, while the lowest curve is the higher bound (Unless it is a sun synchronous orbit [SSO]. In this case the curve above the SSO should be read for higher bound). The altitude bound of the vehicle can also be read directly from the diagram. Thus, the diagram provides two bounds we need to measure against: the inclination bounds and the altitude bounds.

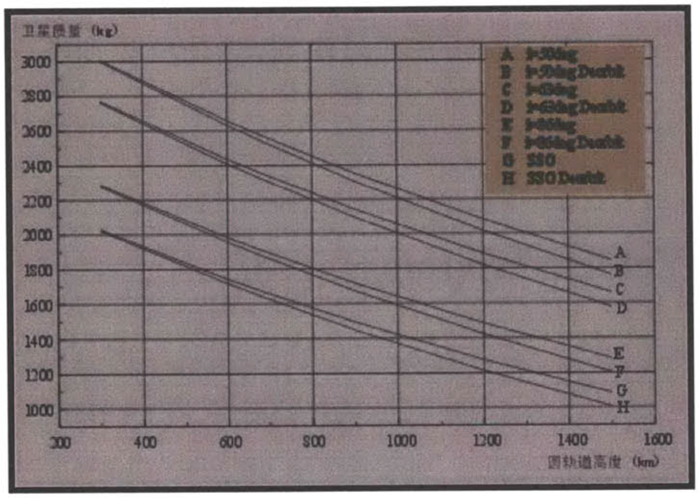


Figure B-8: Launch capability of Long March 2C.

The other physical limit on launch capability is dimensions of the launch vehicle's fairing. Fairing is where the payload of the launch vehicle is stored. The satellite to be launched must fit in the fairing or otherwise it cannot be launched even if its mass is lower than the vehicle's lifting capability. Figure B-9 shows a typical fairing diagram. From the data provided by the diagram, the volume of the fairing can be easily estimated. By comparing the volume of the satellite with the internal volume of the fairing, we will know whether the fairing can accommodate the satellite.

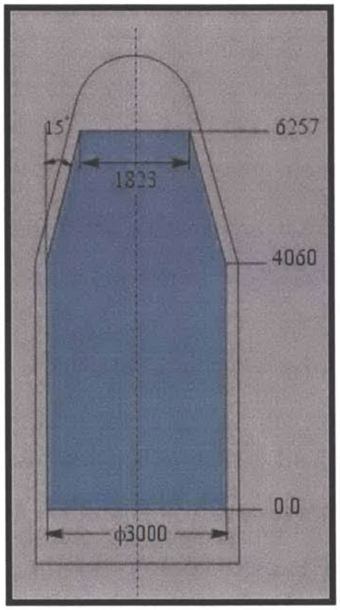


Figure B-9: Fairing dimensions of Long March 2C.

LVM checks the satellite design against the three limits mentioned above: inclination, altitude, and fairing dimension. If the satellite design is within the range of these limits, then we interpolate the type of diagrams in Figure B-8 to find the payload mass the launch vehicle can lift to the designed orbital altitude. If the payload mass is larger than satellite mass, and the fairing volume is larger than satellite volume, then the launch vehicle is recognized as a capable vehicle and added to an array recording capable launch vehicles. To find how many satellites can be sent up per vehicle (*SPV*), we use the following simple expression, in which M_{PL} is payload mass, $V_{fairing}$ is fairing volume, M_{sat} is satellite mass including insertion fuel, and V_{sat} is satellite volume including insertion fuel,

$$SPV = \min\left(\text{floor}\left(\frac{M_{PL}}{M_{sat}} \right), \text{floor}\left(\frac{V_{fairing}}{V_{sat}} \right) \right) \tag{B.49}$$

so that the lower of the mass limit and volume limit is taken. The number of launches to send up the entire constellation is found as

$$N_{launch} = \text{ceiling}\left(\frac{N_{sat}}{SPV}\right) \qquad \text{(B.50)}$$

The information sources for launch capabilities also gives the cost per launch for each launch vehicle. Then the total launch cost C_{launch} is simply

$$C_{launch} = C_{per\ launch} N_{launch} \qquad \text{(B.51)}$$

After checking the capabilities of all six launch vehicles, the array recording the capable launch vehicles and their cost information is scanned. The capable vehicle with lowest cost is chosen to be the selected launch vehicle for the design, and its information and technical data are returned to SF.

Since launch vehicles such as Ariane 5 can lift 6 tons of payload to the geostationary transfer orbit (STO), it is hard to imagine any design is unable to find a launch vehicle capable of lifting it to the much lower LEO orbits. In the unlikely event that the satellite cannot find a capable launch vehicle, SF will set its capability in term of simultaneous users supported by a satellite to zero. Otherwise, the satellite capability needs to be calculated in the capacity modules as introduced in the following section.

B.7 Capacity Modules (CM)

The capacity modules calculate the number of simultaneous users a satellite can support. As described in the thesis, there are two major types of modulation schemes: MF-TDMA and MF-CDMA. Each scheme requires a different approach in capacity calculation. Therefore, CM is divided into five subroutines. The first three subroutines together calculate the capacity of MF-TDMA scheme, and the rest two subroutines calculate the capacity of MF-CDMA scheme. Before introducing the computer codes, we will look at the mathematical equations for the capacity calculation. In the paragraphs below, de Weck and Chang give the final equations that are used in the code. A paper was written by de Weck and Chang to describe the physics behind these equations and to give a more thorough derivation. [deWDC03b]

For MF-TDMA, we first need to find the total data rate for FDMA carriers per cell. There are two possible limits on the data rate – power limit and bandwidth limit. The FDMA data rate per FDMA carrier due to power limit can be calculated using link budgeting, where R_{FDMA} stands for data rate per FDMA carrier, $Power_{cell}$ for transmitter power per cell, N_{FDMA} for number of FDMA carriers per cell, G_t for transmitter gain, G_r for receiver gain, k for Boltzmann's constant, T_s for system temperature, E_b/N_0 for bit energy to noise ratio, L_{tot} for total loss along the transmission path, and *margin* for link margin

$$R_{FDMA} = \frac{\frac{Power_{cell}}{N_{FDMA}} G_t G_r L_{tot}}{kT_s \, {}^{E_b}\!/_{N_0} \, margin} \tag{B.52}$$

Moving N_{FDMA} to the left-hand side of the equation gives the total data rate of all the FDMA carriers per cell defined by power limit

$$R_{FDMA} N_{FDMA} = \frac{Power_{cell} G_t G_r L_{tot}}{kT_s \, {}^{E_b}\!/_{N_0} \, margin} \tag{B.53}$$

To find data rate per cell due to bandwidth limit, we first write the data rate per FDMA channel defined by bandwidth limit. Let BW_{cell} denotes bandwidth per cell (= satellite bandwidth / cluster size), M denotes signal modulation level, β for Nyquist filter rolloff factor, normally ranging from 0.2 to 0.5, B_T for frequency channel bandwidth, and B_g for guard bandwidth, then

$$R_{FDMA} = \frac{\frac{BW_{cell}}{N_{FDMA}} \log_2 M}{1+\beta} \left(\frac{B_T}{B_T + B_g} \right) \tag{B.54}$$

Moving N_{FDMA} to the left-hand side of the equation gives the total data rate of all the FDMA carriers per cell defined by bandwidth limit

$$R_{FDMA}N_{FDMA} = \frac{BW_{cell}\log_2 M}{1+\beta}\left(\frac{B_T}{B_T+B_g}\right) \tag{B.55}$$

In this equation, we already know BW_{cell}; M is 4 if QPSK is used, and β is set to 0.26 as a constant. In Iridium, the frequency domain is divided so that

$$\frac{B_T}{B_T+B_g} = \frac{41.67\text{MB}}{41.67\text{MB}+1.236\text{MB}} = 0.9712 \tag{B.56}$$

We assume this division applies to all MF-TDMA systems and use the value of 0.9712 in Equation (B.55).

To find the number of TDMA channels, we refer to the geometry of time distribution. In the geometry, let FL denote frame length, FIL denote framing time slot length, TGL denote total guard slot length, and R_{user} denote individual user datarate. It is not difficult to perceive the following relation

$$N_{TDMA} = \frac{R_{FDMA}\left(1-\frac{FIL}{FL}\right)}{R_{user}\left(1+\frac{TGL}{FL-FIL-TGL}\right)} \tag{B.57}$$

Per theory of MF-TDMA modulation scheme, the total number of MF-TDMA channels is the product of N_{FDMA} and N_{TDMA}. Then we will get

$$N_{FDMA}N_{TDMA} = N_{FDMA}\frac{R_{FDMA}\left(1-\frac{FIL}{FL}\right)}{R_{user}\left(1+\frac{TGL}{FL-FIL-TGL}\right)}$$

$$= N_{FDMA}R_{FDMA}\frac{\left(1-\frac{FIL}{FL}\right)}{R_{user}\left(1+\frac{TGL}{FL-FIL-TGL}\right)} \qquad \text{(B.58)}$$

In this equation, $N_{FDMA}R_{FDMA}$ is the lower of the results from Equation (B.53) and (B.55). To find the fractional term in the equation, we use the design of Iridium and assume it is typical of MF-TDMA systems. In Iridium, the time domain is divided so that

$$\frac{1-\frac{FIL}{FL}}{1+\frac{TGL}{FL-FIL-TGL}} = \frac{1-0.192}{1+\frac{0.04}{1-0.192-0.04}} = 0.77 \qquad \text{(B.59)}$$

Therefore, the capacity of a MF-TDMA system can be found. For Iridium, equation (B.58) gives a capacity of 905 simultaneous users per satellite.

For MF-CDMA system, omitting the detailed derivations, we arrive at an equation for the number of simultaneous users per cell N_c, where T denotes number of CDMA carriers in the satellite bandwidth, B_{sat} denotes satellite bandwidth, B_g denotes guard band between CDMA carriers, R_{user} denotes individual user data rate, α of value 0.5 represents the expected value of voice channel activity state, f denotes neighboring user interference factor, E_b/N_0 represents the ratio of bit energy to noise caused along the link, and E_b/I_{tot} represents the ratio of bit energy to noise including both N_0 and interference noise.

$$N_c = T + \left[\frac{B_{sat}-TB_g}{R_{user}}\frac{1}{\alpha(1+f)}\right]\left[\left(\frac{E_b}{I_{tot}}\right)^{-1} - \left(\frac{E_b}{N_0}\right)^{-1}\right] \qquad \text{(B.60)}$$

and an equation for E_b/N_0 for each individual link is

$$E_b/N_0 = \frac{\frac{Power_{cell}}{N_c} G_t G_r L_{tot}}{kT_s R_{user} margin} \tag{B.61}$$

or, if move N_c to the left-hand side,

$$E_b/N_0 \, N_c = \frac{Power_{cell} G_t G_r L_{tot}}{kT_s R_{user} margin} \tag{B.62}$$

Substituting (B.61) into (B.60) and solving for N_c, we find the following expression

$$N_c = \frac{T + \frac{B_{sat} - TB_g}{R_{user}} \frac{1}{\alpha(1+f)} \frac{I_{tot}}{E_b}}{1 + \frac{B_{sat} - TB_g}{R_{user}} \frac{1}{\alpha(1+f)} \left(\frac{Power_{cell} G_t G_r L_{tot}}{kT_s R_{user} margin} \right)^{-1}} \tag{B.63}$$

As was mentioned before the equations were introduced, five subroutines are written to convert the above mathematical expressions into the simulation. The first three subroutines are for MF-TDMA, among which, the first subroutine `linkRate.m` returns the value of $R_{FDMA}N_{FDMA}$ in (B.53). The second subroutine `BWLimit.m` returns the value of $R_{FDMA}N_{FDMA}$ in (B.55). The lower of these two values defines the bound and is input into the third subroutine `MF_TDMA.m`, which uses (B.58) to find the total number of MF-TDMA channels supported by a satellite.

The next two subroutines find the capacity of a MF-CDMA system. The first of them `linkEbNo.m` gives $(E_b/N_0)N_c$ in (B.62). Substituting this result to the last subroutine `MF_CDMA.m`, N_c in (B.63) is calculated. The satellite capacity is the product of N_c and the number of cells N_{cell} calculated in (B.21).

$$C_{sat} = N_c \times N_{cell} \tag{B.64}$$

One more thing worth mentioning despite the omission of the derivation of the equations is convolutional coding. In convolutional coding, redundancy cleverly coded into transmitted information reduces transmit power required for a specific bit error probability. This reduction process has two important parameters, code rate r and constraint length K. Code rate r is defined by the ratio between the original information bits k and the redundantly coded content bits n,

$$R_c = k/n \tag{B.65}$$

The bit energy to mean total noise power spectral density ratio E_b/I_{tot} corresponding to several bit error probabilities, p_b, are listed in Table B.2 for soft-decision Viterbit decoding. [JKWE00]

p_b	E_b/I_{tot} uncoded	$R_c = 1/3$		$R_c = ½$			$R_c = 3/3$		$R_c = ¾$	
		$K = 7$	$K = 8$	$K = 5$	$K = 6$	$K = 7$	$K = 6$	$K = 8$	$K = 6$	$K = 9$
10^{-3}	6.8	4.2	4.4	3.3	3.5	3.8	2.9	3.1	2.6	2.6
10^{-5}	9.6	5.7	5.9	4.3	4.6	5.1	4.2	4.6	3.6	4.2
10^{-7}	11.3	6.2	6.5	4.9	5.3	5.8	4.7	5.2	3.9	4.8

Table B.2: Coding gain E_b/N_0 (dB-b^{-1}) for soft-decision Viterbi decoding, QPSK

From Table B.2, the values of E_b/N_0 in (B.53) and of E_b/I_{tot} in (B.63) can be read and used in the simulation.

The satellite capacity of either the MF-TDMA system or MF-CDMA system is returned to SF. Then in SF, the system capacity in term of the number of simultaneous users supported by the entire constellation is calculated. The calculation is slightly different for polar constellation and Walker constellations. Because satellites in the polar constellation all need to fly above the poles, at the poles there is a severe overlapping of satellites' footprints. This overlapping causes a reduction in the overall system capacity of polar constellation, which can be represented by the polar overlapping factor (*POL*)of 0.68 for polar constellation. For Walker constellation, *POL* is 1 because Walker constellation covers only below certain latitude and never passes the poles. Therefore the system capacity equation is

$$C_{system} = C_{sat} \times N_{sat} \times POL \tag{B.66}$$

B.8 Total Cost Module (TCM)

The cost module methodically computes the present value of the life-cycle cost of the system. The method is modified on the basis of cost estimating relationships (CERs) in Larson and Wertz [WLJR99]. A step-by-step introduction to the method will be given after we introduce the inputs and output of the module. The inputs include the number of satellites in the constellation, number of orbital planes, orbital altitude, antenna weight, communication electronics weight, spacecraft bus dry weight, satellite mass (wet weight), beginning-of-life power, flight software thousand lines of code, ground software thousand lines of code, designed life of space segment, initial deployment time, number of gateways, number of operations and support personnel, AKM type, AKM dry weight, AKM impulse, discount rate, minimum launch cost, and ISL datarate. The output of the module is the total present value of the life-cycle cost (LCC) of the designed system. All cost terms in this module are in unit of thousand of U.S. dollars in fiscal year 2002.

In this module, it takes totally 16 steps to account for the LCC of the system. The first step sets space mission characteristics. Most of these characteristics are design variables, constants, or system parameters obtained in previous modules. There are two exceptions: payload type and number of spare spacecraft. Apparently, the payload type is communication. A spare satellite is typically launched into each orbital plane at altitude lower than that of the regular orbit so that it is ready to replace a failed satellite in that orbital plane. Therefore the number of spare spacecraft is set to the number of orbital planes.

The second step accounts for the hardware cost of the research, development, test and evaluation (RDT&E) phase. As the name suggests, this phase occurs very early in the system life-cycle. It is a breakdown of the costs of antenna, communication electronics, spacecraft bus, and apogee kick motor. Each cost is in relation with the weight of that particular component except that the AKM cost is linear with the AKM impulse.

If antenna weight is M_{ant}, then the antenna cost is found to be

$$C_{ant} = 1015 M_{ant}^{0.59} \tag{B.67}$$

The communication electronics cost is

$$C_{CE} = 917 CEW^{0.7} \tag{B.68}$$

where CEW is weight of communication electronics. The cost of spacecraft bus is based on $SCBDW$, the dry weight of spacecraft bus

$$C_{SC\,bus} = 16253 + 110 SCBDW \tag{B.69}$$

The AKM weight depends on AKM impulse and also on the AKM type. If the AKM is spin-stabilized, then the cost is

$$C_{AKM} = 490 + 0.0518 J_{AKM} \tag{B.70}$$

If the AKM is 3-axis stabilized, which is more popular for current LEO communication satellite design, then the cost is

$$C_{AKM} = 0.0156 J_{AKM} \tag{B.71}$$

The total hardware cost of the RDT&E phase is the sum of the above component costs. Because the relations above are developed using 1992 USD value, de Weck and Chang converted them to 2002 USD value by the inflation rate of 1.369. Therefore the hardware cost is

$$RDTEHC = \left(C_{ant} + C_{CE} + C_{SC\,bus} + C_{AKM}\right) \times 1.369 \tag{B.72}$$

The third step is to find to find theoretical first unit (TFU) hardware cost. This step is the same as the previous step except the component costs are calculated differently as follows

$$C_{ant} = 20 + 230 M_{ant}{}^{0.59} \tag{B.73}$$

$$C_{CE} = 179 CEW \tag{B.74}$$

$$C_{SC\,bus} = 185 SCBDW^{0.77} \tag{B.75}$$

For spin-stabilized AKM,

$$C_{AKM} = 58 AKMDW^{0.72} \tag{B.76}$$

For 3-axis stabilized AKM,

$$C_{AKM} = 0.0052 J_{AKM} \tag{B.77}$$

The rest of step 3 is the same as step 2. The TFU hardware cost is

$$TFUHC = \left(C_{ant} + C_{CE} + C_{SC\,bus} + C_{AKM}\right) \times 1.369 \tag{B.78}$$

Step 4 is to find the hardware cost of every spacecraft produced. This step includes the learning curve phenomenon that accounts for production cost reduction as the production quantity increases. The reduction in cost is due to economies of scale, set up time, and human learning. The total production cost of N units is modeled as

$$C_N = TFU \times N^{1-\log_2(100\%/S)} \tag{B.79}$$

The learning curve slope S represents the percentage reduction in cumulative average cost when the number of production units is doubled. Larson and Wertz [WLJR99] recommend the values shown in Table B.3 for learning curve slope.

Number of units	Learning curve slope
≤10	95%
10< and ≤50	90%
50<	85%

Table B.3: Learning curve slope values

The cost of the first unit is C_1 given by equation (82) with $N = 1$; the cost of the second unit is $C_2 - C_1$ where C_2 is given by equation (82) with $N = 2$; the cost of the third unit is $C_3 - C_2 - C_1$, so on and so forth. The hardware costs of all units are assigned to elements of an array called UHC.

Step 5 finds aerospace ground equipment cost for RDT&E. The cost is expressed in a simple linear relation

$$AGEC = 0.11(RDTEHC + TFUHC) \tag{B.80}$$

Step 6 finds total program level cost for RDT&E and all units including TFU. First, program level cost for RDT&E is

$$PLC_{RDT\&E} = 0.36RDTEHC \tag{B.81}$$

Program level cost for all units is

$$PLC_{u} = \sum \mathbf{UHC} \tag{B.82}$$

Total program level cost is

$$PLC_{tot} = PLC_{RDT\&E} + PLC_{u} \tag{B.83}$$

Step 7 is to find launch operations and orbital support cost. For launch without the use of AKM, the cost per satellite is

$$LOOSC = 2.51M_{sat} \tag{B.84}$$

For launch with AKM, the cost per satellite is

$$LOOSC = 64 + 1.44M_{sat} \tag{B.85}$$

The total cost of all satellite units is

$$LOOSC_{tot} = LOOSC \times N_{sat} \times 1.369 \tag{B.86}$$

Step 8 finds flight software cost by scaling the thousand lines of code.

$$C_{FS} = 375 \times FSKLOC \times 1.369 \tag{B.87}$$

Step 9 accounts for the minimum launch cost found in the launch vehicle module.

$$C_{LV} = C_{launch\ min} \tag{B.88}$$

Step 10 finds ground software cost assuming the language used is Unix-C.

$$C_{GS} = 190 \times GSKLOC \times 1.369 \tag{B.89}$$

Step 11 is to find total ground segment development cost, which is consisted of costs of all the gateways and two command centers. Larson and Wertz [WJLR99] suggest that the cost of developing a gateway (or ground station) has a breakdown as listed in Table B.4.

Ground Station Element		Development Cost as Percent of Software Cost (%)
Facilities (FAC)		18
Equipment (EQ)		81
Software (SW)		100
Logistics		15
System level		
	Management	18
	Systems engineering	30
	Product assurance	15
	Integration and test	24

Table B.4: Ground segment development cost distribution

So the ground station development cost is simply

$$GSDC = (18 + 81 + 100 + 15 + 18 + 30 + 15 + 24)\% \times C_{GS} \tag{B.90}$$

In addition to gateways, the system also needs command centers to control network and satellite operations. Two command centers are assumed for the system. The cost of each command center is the average of seven actual systems' command center costs drawn from their FCC filings. These seven systems are @contact, ARIES, GEMnet, Globalstar, Orbcomm, Starnet, and VITA. The average cost is 11.856 million USD. Therefore the total ground segment development cost is the sum of the costs of all the gateways and two command centers.

$$GSDC_{tot} = N_{GW} \times GSDC + 2 \times CCC \tag{B.91}$$

Step 12 is to find initial development cost (*IDC*), which is the cost up to the onset of the service of the system. To get *IDC*, we need to sum up all the costs we have calculated previously.

$$IDC = RDTEHC + \sum_{i=1}^{size\ of\ \mathbf{UHC}} \mathbf{UHC}_i + AGEC + PLC_{tot} + LOOSC_{tot} + C_{FS} + GSDC_{tot} + C_{LV} \tag{B.92}$$

In order to find the present value of the cost, a cost distribution over development time needs to be modeled first. To be clear, the life-cycle of the system is consisted of two stages. The first stage is the initial development time (IDT) that starts with the RDT&E stage of the system, and extends till the deployment of the entire system. The second stage is the space segment life, which starts with the completion of system deployment and onset of service, and lasts until the end life of the satellites. In step 13 we look at the cost distribution in IDT. Larson and Wertz [WLJR99] suggest finding the cost spreading by a function of the form

$$F(S) = A[10 + S((15 - 4S)S - 20)]S^2 + B[10 + S(6S - 15)]S^3 + [1 - (A + B)](5 - 4S)S^4 \tag{B.93}$$

where *F*(*S*) is the fraction of cost consumed in time *S*, *S* is the fraction of the total time elapsed, and *A* and *B* are empirical coefficients. Coefficients *A* and *B* depend on percentage of expenditure at schedule midpoint. For project involving more than two satellites, 50% expenditure at schedule midpoint is suggested, and the corresponding *A* and *B* are 0 and 1.00. Using these values, it is easy to find the cost per year for each year during the IDT. These values are stored in array $\mathbf{C}_{\mathbf{year}}$. As mentioned above, we assume the IDT to be a constant at 5 years.

Step 14 gives operation and support cost per year during space segment life time. The yearly maintenance cost per gateway is

$$C_{maint} = 0.1 \times (SW + EQ + FAC)/year \tag{B.94}$$

For personnel cost, contractor labor is estimated to cost \$140K/staff year. Also 150 staff members are assumed to keep the business running, besides the personnel at the gateways. Summing the maintenance and personnel costs, the total operation and support cost per year is

$$C_{OS\ per\ year} = C_{maint} \times N_{GW} + 140(N_{personnel} + 150) \tag{B.95}$$

In step 15, $C_{OS\ per\ year}$ is distributed over space segment life time. Because the maintenance and personnel costs are assumed constant throughout the years, we simply assign the value of $C_{OS\,per\,year}$ to each year in the space segment life time. After appending the space segment life time yearly cost to it, $\mathbf{C}_{\mathbf{year}}$ covers the entire life-cycle of the system.

$$C_{tot} = \sum_{i=1}^{size\ of\ \mathbf{C}_{\mathbf{year}}} \mathbf{C}_{\mathbf{year}\,i} \tag{B.96}$$

In step 16, an additional fee is accounted as 10% of the total cost. So the final total cost C_{tot} is

$$C_{tot} = (1 + 0.1) \sum_{i=1}^{size\ of\ \mathbf{C}_{\mathbf{year}}} \mathbf{C}_{\mathbf{year}\,i} \tag{B.97}$$

The value of the total cost is returned to SM.m as the life-cycle cost.

B.9 End User Terminal Module (EUTM)

EUTM estimates the unit cost and one time activation fee of a paging end user terminal given certain input characteristics. The inputs to the module are the number of characters that can be sent in a message, whether the terminal is desired to be one-way or two-way, whether it has a keyboard, the size of its physical volume and its memory storage level. For each input there is more than one level that can be inputted. They are as follows:

- For the number of characters, the input can be 1-100 characters, 101-250 characters or 251-500 characters per message
- The one-way or two-way input is a Boolean variable representing either that the pager is one-way or two-way.
- The keyboard input is also a Boolean representing the presence or absence of a keyboard. Note that given advances in current technology it is possible to have a virtual keyboard by which one can input letters without the traditional keyboard format.
- The physical volume parameter can take the values of 1 to 4.9 inches cubed or 5 to 8.9 inches cubed
- The memory storage level input can take values of 1 to 5000 bytes, 5001 bytes to 100 KB or 200 KB to 4.5 MB

A Design of Experiments (DOE) analysis was conducted on a number of pagers that have attributes within the various ranges as detailed above. Note that each of the inputs described above are known as the factors within the DOE analysis. Also as detailed above, each factor can take different levels of values. The DOE facilitates a formulaic, decisive approach to deciphering the output of a system with many inputs that can take more than one level of input values. In this case the final output is the pager end user terminal unit cost plus a standard one time activation fee. The formulas resulting from the DOE process which incorporate each level of each input attribute are modeled into

MATLAB such that through choosing a combination of any level of each input variable one can gain a value for the end user terminal cost plus one time activation fee for a terminal harboring the characteristics inputted.

Table B.5 demonstrates the paging end user terminals data set. It details all the pagers assessed and the values for each factor for each pager analyzed. The unit cost and monthly charge for each pager are also detailed in Table B.5. Across all the factors and costs reported, the average value of each factor and the costs are reported in the final row of Table B.5. This will be instrumental in calculating the costs of the pager given specific inputted factor levels.

Pager Name	**Trt/Rec** (T+R=1; T = 0)	**Keyboard** (yes = 1, no = 0)	**Number of characters**	**Volume** (inches^3)	**Memory** (bytes)	**Unit cost** (including activation fee; 2002 US $)	**Monthly Charge** (2002 US $)
MBR850	0	0	20	2.5	1200	65	20
MPE	0	0	20	3.680	320.000	30.000	20.000
MBF	0	0	20	3.780	320.000	40.000	20.000
MAE	0	0	240	5.030	4560.000	70.000	30.000
T900	1	1	500	5.400	70,000.00	99.000	15.000
ALII	1	0	500	5.280	4,000,000.00	70.000	15.000
T350	0	0	250	5.280	1600.000	30.000	17.000
PF1500	1	0	250	4.449	100,000.00	50.000	17.000
Jazz	0	0	250	2.682	2200.000	40.000	60.000
Average			**227.78**	**4.23**	**464,466.67**	**54.89**	**23.78**

Table B.5: Paging End User Terminals Data Set

Table B.6 details the specific amount by which each level of each factor changes the unit cost plus activation fee and the monthly charge respectively. This was calculated as follows: Taking level 1 of the factor of number of characters for instance (i.e., 1 to 100 characters) the average of the unit cost plus activation fee parameter for all the pagers which have level 1 values for their number of characters parameter is calculated. The average of the unit cost plus activation fee for all the pagers across all levels of this factor (i.e., the 7th column and final row element of Table B.5) is subtracted from the value previously calculated for the average cost for the number of characters level 1 cost values. The result indicates how much the average unit cost plus activation fee value would change if a pager with the level 1 value for the number of characters factor was used.

Table B.6 details in entirety how much both the unit cost plus activation fee parameter and the monthly charge parameter's average values reported in the last row of Table B.5 would change if any level of each factor is inputted into the EUTM to create a desired pager unit. The MATLAB implementation of this module incorporates every possible combination of factors and their respective levels and given the values in Table B.6 consequently calculates what the final values for the unit cost plus activation fee and the monthly charge would be given the inputted factor levels.

Factor	Level	Unit cost + activation fee	Monthly Charge
#char	level 1 (1-100)	-9.889	-3.778
	level 2 (101-250)	-7.389	7.222
	level 3 (251-500)	29.611	-8.778
tran/rec	level 1 (0)	-9.056	-2.778
	level 2 (1)	18.111	-8.111
keyboard	level 1 (0)	-5.500	1.097
	level 2 (1)	44.111	-8.778
volume	level 1 (1 to 4.9 in^3)	-9.889	3.622
	level 2 (5 to 8.9 in^3)	12.361	-4.528
memory	level 1 (1 to 5000) bytes	-9.056	4.056
	level 2 (5001bytes - 100 KB)	19.611	-7.778
	level 3 (200KB - 4.5MB)	15.111	-8.778

Table B.6: Pager Data Set Main Effect Calculations

Hence for this analysis the chosen pager resulted in the following unit cost plus activation fee (the monthly charge is calculated but not reported as this largely depends on the lifecycle cost of the system used to provide connectivity and would thus be dependent on the system operator of the proposed system to set). Note all values shown in the calculations that follow are taken from Tables B.5 and B.6.

Average unit cost plus activation fee =	$54.89
1 -100 characters changes average value by	- $9.889
Two way functionality changes average value by	+ $18.111
No keyboard present changes average value by	- $5.500
Volume of 1 – 4.9 inches cubed changes average value by	- $9.889
Memory capacity of 1 to 5000 bytes changes average value by	- $9.056
Resulting cost for pager with the above factor levels =	**$38.67**

This value of $38.67 is what an end user would have to pay for a pager with the levels of each factor as described above. The above attributes were the attributes of the pager selected as the pager of choice in the system analysis and contributed to the green vertical cost to the user line in Figure 3-5. If the values for each level were to be changed by the system designer the resulting cost for the pager unit would change. The EUTM can be used to decipher the cost of a pager unit given any combination of levels for each factor.

B.10 Total Number of Subscribers for Pareto Architecture

The following analysis demonstrates how the total number of subscribers value of 81, 259, 200 subscribers was arrived at for the most ideal Pareto optimal architecture resulting from the system simulation. The capacity of the most ideal Pareto architecture is 16,720 users as shown in Table 3.9 for design number 8. Recall that as shown in Table 3.4 the data rate per user channel is 4800 bits per second. Also recall that each SMS message can hold up to 160 characters, and there are 8 bits in every character and thus (160 * 8) = 1280 bits in every message. Hence the number of messages per user per second that the Pareto satellite system can accommodate is given by:

$$\frac{4800 bits / user / \sec ond}{1280 bits / message} = 3.75 \text{ messages/second/user} \quad (B.98)$$

With a total capacity of 16, 170 users the system can send the following number of messages per second:

$$3.75 messages / user / \sec ond * 16{,}720 users = 62{,}700 \text{ messages/second} \quad (B.99)$$

However the satellite system will most likely not operate at 100% capacity at all times. For systems such as this, the fraction of available capacity that is actually used is normally approximately 15%. [deWDC03a] Hence the number of messages that the system will send per second accounting for this average 15% usage equals:

$$\frac{15}{100} * 62{,}700 messages / \sec ond = 9{,}405 \text{ messages per second} \quad (B.100)$$

With knowledge in hand of the number of messages that the system will send per second, the number of seconds in a day and the number of messages that each user will send and receive per day, one can now calculate the total number of subscribers to the satellite system as follows:

$$\frac{9{,}405 messages}{1 \sec ond} * \frac{86{,}400 \sec onds}{1 day} * \frac{1 user / day}{10 messages} = 81, 259, 200 \text{ subscribers} \quad (B.101)$$

Hence the Pareto optimal system resulting from the simulation in this analysis could serve 81, 259, 200 subscribers when 15% of the total system capacity is being utilized.

B.11 Output assignment and Postprocessing

The last step in the for-loops of the SF is to assign the values of the objectives to the objective vector **J**, the benchmarking parameters to **B**, and requirements to **r**. This concludes the nested for-loop.

The post-processing is carried out at the end of SF. It involves finding the Pareto front of the design space. This character of the design space exploration was introduced in the design space exploration and optimization section of Chapter 3. Before exploring the design space, benchmarking was performed to prove the fidelity of the simulation.

Appendix C

Developing World Survey

As mentioned in Appendix A, for the purposes of this research I developed a survey to act as a relevant and detailed assessment of the digital divide for developing countries. Great care was taken to ensure that the survey was relevant, asked the right questions and would strike the balance between not being too time intensive while still providing an in-depth view of the state of communications technology in the developing world. The survey in its exact form as it appeared to potential respondents via World Wide Web format is shown below in Figure C-1. The survey was sent to one of each of the ITU's 189 member country representatives (many countries have more than one member organization) in the hopes that a statistically significant response rate would be achieved. A reasonable response rate from the survey had the potential to add immense value to my research.

The purpose of this survey was firstly to give a snapshot of the state of development of the telecommunications sector within the country the respondent represents. This would then allow for the identification of the current communication needs of each country surveyed. Additionally, the information from the survey would provide a tangible idea of the role the respondent feels satellites could play in providing communications applications to the underserved in developing and even in developed countries. Another major thrust of the survey was to assess the feasibility of a paging system with a satellite backbone which would provide connectivity in regions currently underserved by communications technologies. Lastly, the survey allowed for the prioritization of the applications viewed as most needed by the respondent along with the identification of barriers impeding growth in the telecommunication sector of the respondent's country.

Potential respondents were informed that participation in the survey was voluntary and that they could decline to answer any or all questions. Also the survey did not have to be filled out at one sitting, responses could be saved and the survey returned to at a later date. Respondents could also decline further participation, at any time. All respondents were informed that anonymity would be ensured by representing all data obtained with the country represented by the respondent as the sole identifier. No personal details of the respondent would have been used when processing and representing the survey results.

Email was the means used to contact potential respondents. Between the ITU member countries not having email addresses or not having a valid email addresses, in all 160 requests to fill out the survey in Figure C-1 were successfully sent out. From that Figure a total of 10 member countries responded after an approximate 3 month period. The ten responses did not represent complete responses from each individual. As a result of the paltry 6% response rate, I was unfortunately not able to use the survey as a resource for my thesis.

The effort was a learning process however and I thought it worthwhile to share the insight I learned. The following would be my recommendations to future researchers seeking to conduct a global survey in the information and communication technologies for development sphere.

1. In the ICT realm, there still is not much organized national data available from one telecommunications source, be it in the public or private sector. In my opinion, a major contributant to my survey's low response rate is that the telecommunication agencies contacted simply did not know the answer to a lot of the questions asked and I would not be surprised if the body to be approached to respond to the answers was not much clearer either.

2. Email should not be the only means of contact, it is best if you can visit the administration you want to interview and interview relevant personnel face to face. Failing that, a phone interview would be the next best medium to pursue.

3. Incentives of some form are essential. My survey did not have an incentive and this could have been another major contributant to the low response rate.

4. No matter the purpose, try to stick to a time limit of less than or equal to 10 minutes for the average person to fill out the survey. Once a potential respondent takes a look at the survey and sees that it will probably take more than 10 minutes, the opportunity to gain a response from him or her may be lost.

5. Do not ask for personal information if at all possible.

6. Have a means by which you can follow up with potential respondents to remind them to fill out the survey.

Assessment of the Digital Divide for Developing Countries

Respondent Data

1. What is your full name?

2. What is your email address?

3. What is your work telephone number?

4. Which country do you represent?

5. Signatory to ITU since when?

6. Is there an Organization of Telecomm domestically and if applicable under what Ministry?

☐ Yes ☐ No

Under which Ministry?

7. What is your position at ITU/in your country's telecomm Ministry/administrative agency?

8. Please indicate whether your country is a stakeholder in an International Satellite organization/s such as: (Intelsat, EutelSat, ArabSat, InmarSat for ex.)

Land Based Wired Communications (including Copper and fiber optics)

9. Percentage of households with electricity?

9. Percentage of households with electricity?

○ 1-5%
○ 6-10%
○ 11-15%
○ 16-20%
○ 21-25%
○ 26-30%
○ 31-35%
○ 36-40%
○ 41-45%
○ 46-50%
○ 51-55%
○ 56-60%
○ 61-65%
○ 66-70%
○ 71-75%
○ 76-80%
○ 81-85%
○ 86-90%
○ 91-95%
○ 96-100%

10. Cost of a basic radio that has AM/FM functionality only (in US $)? (example: $5)

11. Estimation of growth rate of terrestrial PSTN *subscribers* in the last four years (i.e. 2000-2001-2002-2003)? (example: 2000 – 10% subscriber growth rate (gr) ; 2001 – 8% subscriber gr; 2002- 7% subscriber gr; 2003 – 4% subscriber gr.)

12. Estimation of growth rate of PSTN *land telephone lines* over the last 5 years. (example: 2000 – 10% growth rate of land telephone lines (gr) ; 2001 – 8% gr; 2002- 7% gr; 2003 – 4% gr)

Terrestrial Cellular Communications

13. Number of mobile telephone numbers issued? (example: As of this year there have been approximately 2,453,678 mobile telephone numbers issued)

14. A map of cellular coverage as of 2004 (where available please provide internet URL) – or estimate percentage of landmass where terrestrial cellular coverage exists.

15. Estimation of growth rate of percentage land mass coverage by terrestrial cellular systems over the last 5 years. (example: "Over the last 5 years Tanzania has experienced a growth rate of 17% in the percentage land mass covered by terrestrial cellular systems.")

16. Estimation of the number of mobile users your country has had over the last four years (2000-2001-2002-2003). (example: 2000 – 100,000 mobile users; 2001 – 150,090 m. users; 2002- 476,450 m. users; 2003 – 876,543 m. users)

17-22. Current mobile telephone protocols in use by your Telecom industry?* (more than one answer may be indicated)

☐ GSM-9.6 kbit/s
☐ IS-136/TDMA-57.6 kbit/s
☐ PDC-28.8-kbit/s
☐ IS-95A/CDMA-64kbit/s
☐ GPRS- 171.2 kbit/s
☐ IS-95B/CDMA-115kbit/s

* the kbit/s Figure given represents the maximum speed that the mobile protocol operates within.

Satellite based communications

23. Number of Satellite Television receivers per 100 people? (example: 24 satellite television receivers per 100 people)

24. What role if any are satellite services playing in assisting to bridge the digital divide in your country?

Market, Competition, Affordability and Regulatory Issues

25. Internet access tariff in US $ (for sample 20 hours per month package)

26a. For Mobile phone service (please give any requested costs in US $)

i. What is the percentage of prepaid subscribers?

ii. What is the cost of sending one SMS?

iii. What is the cost of sending one MMS?

iv. What is the cost of a basic mobile phone?

26b. Internet access (please give costs in US $)
i. What is the cost of one hour in a cybercafe?

ii. What is the cost of Wi-Fi access for one hour (if available)

iii. What is the cost of a basic desktop computer?

27. Number of Internet Users per 100 Inhabitants (Internet user is defined as someone who uses the internet at least once a month whether it is via his/her own equipment or not).

28. Telecom market competition in your country? Pick one.

○ a. Monopoly (single provider) Please provide name:

○ b. Oligopoly (few providers) Please provide names:

○ c. Free Market competition (Many, >3 providers). Give names of three main Telecom providers:

29. What percentage of your population would you say is below the poverty line (poverty line defined as living on less than US $2 a day? (example: 28%)

Potential for a low cost SMS based paging system

30. Estimation of the amount (specific components outlined below) an individual earning an average salary would be willing to pay for a paging service such as short messaging service (SMS) in regions where no other communication option exists?

a. For purchase of a paging/SMS only type device (end user terminal)

b. For monthly subscription fee that comes with 300 SMS messages for example?

c. For cost per message when not dealing with prepaid SMS packages?

Particular Needs and Challenges

31. Are you of the opinion that there are a sufficient number of local websites providing national news, tending to civic matters and addressing public and private sector concerns that are available in the countries local and/or official language?
(example: yes/no)

32. Are problems currently being faced due to insufficient cellular/telecomm coverage, if so what are three of the main issues contributing to these problems?
a. Issue 1:

b. Issue 2:

c. Issue 3:

33. What is the current state of your country's communication infrastructure?

☐ 1. much improved over the last 10 years but still deeply lacking, deepest issue currently lies with...

☐ 2. current situation in need of injection of funds and proper planning but can be ameliorated if such resources become available

☐ 3. deeply lacking, terrestrial connectivity media absent, satellite communications applications only real answer

☐ 4. other

Particular Needs and Challenges (continued)

34. What are major potential benefits of satellite based telecommunications services in your country? (These could be services that are either not being currently provided or are not being offered at desirable levels.) Please cite specific examples (e.g. person-to-person communications, telemedicine, tele-education, emergency service response, e-commerce, e-government, earth observation [e.g. monitoring of fish populations, water level and water cleanliness observation and hence management, etc...]).

35. What are the major impediments to the use of satellite based communications services in your country? Please be as specific as you can.

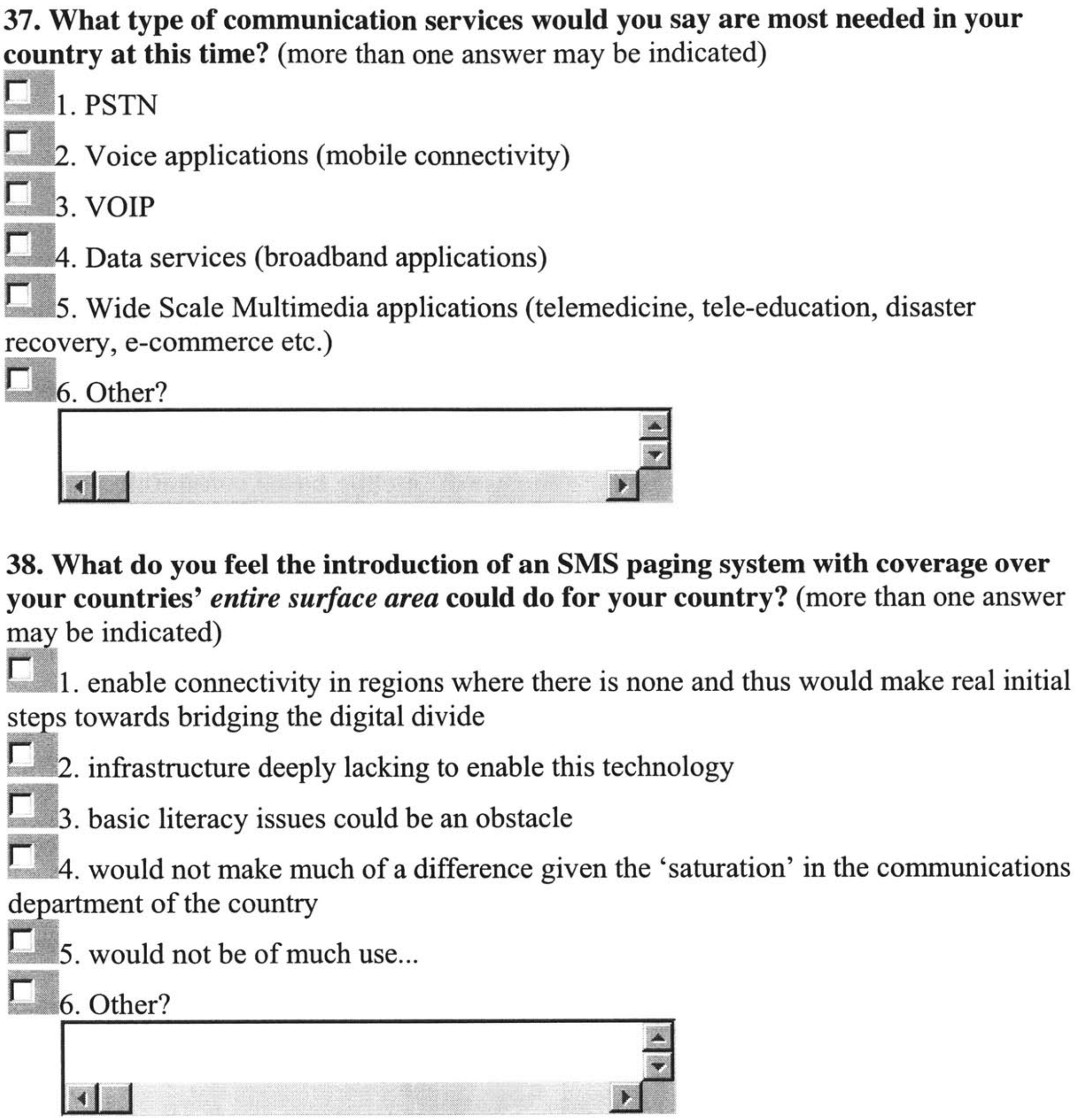
36. What is the historical context of your country's communications industry?

○ 1. A monopoly/oligopoly is in existence, this provider offers a diverse array of services, with cost being the only debilitating factor.

○ 2. A monopoly/oligopoly is in existence with a limited number of available services. This monopoly/oligopoly presents high barriers to new entrants.

○ 3. There are no incentives for people to invest in the communications industry, current regulatory atmosphere too strict

○ 4. Other?



37. What type of communication services would you say are most needed in your country at this time? (more than one answer may be indicated)

☐ 1. PSTN

☐ 2. Voice applications (mobile connectivity)

☐ 3. VOIP

☐ 4. Data services (broadband applications)

☐ 5. Wide Scale Multimedia applications (telemedicine, tele-education, disaster recovery, e-commerce etc.)

☐ 6. Other?

38. What do you feel the introduction of an SMS paging system with coverage over your countries' *entire surface area* could do for your country? (more than one answer may be indicated)

☐ 1. enable connectivity in regions where there is none and thus would make real initial steps towards bridging the digital divide

☐ 2. infrastructure deeply lacking to enable this technology

☐ 3. basic literacy issues could be an obstacle

☐ 4. would not make much of a difference given the 'saturation' in the communications department of the country

☐ 5. would not be of much use...

☐ 6. Other?

Figure C-1: Developing World Survey

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