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# Metric for Systems Evaluation and Design of Satellite-Based Internet Links

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**A metric of the cost to maintain a 1.544-Mbps link is developed for systems evaluation of satellite-based Internet links. The major limiting factors addressed are satellite power resources, achievable link margins, rain attenuation, and distributed market models. The life-cycle costs are estimated for satellite design and construction, launch, insurance, gateways, gateway and control center operations, and terrestrial Internet connections. The cost per T1 minute to obtain a given internal rate of return is calculated from the achievable capacity and cost estimates. The metric is evaluated for five modeled systems in geosynchronous and low Earth orbits to demonstrate the applicability of the metric to the systems engineering and design process. The metric shows the sensitivity of the systems to market variations and illustrates the criticality of beam placement and deployment strategies to minimize risk.**

## Nomenclature

$C_T$ = total system cost, fiscal year 1996, dollars (FY 96 $)
$F$ = fraction of cost consumed
$L$ = learning curve factor
$N$ = number of production units
$NR$ = nonrecurring cost, FY 96 $
$R$ = recurring cost, FY 96 $
$S$ = learning curve slope
$T$ = fraction of total time elapsed (fraction)

## Introduction

IN an era where a large portion of the world depends on high technology for its day-to-day activities, information is power. The Internet has become the newest manifestation of the power of information. As a disseminator of information, it has no parallel.

In light of this, it was not surprising that, when the Federal Communications Commission (FCC) deadline for filing an application to construct and launch broadband satellite communications systems passed on Sept. 29, 1995, 14 companies had filed applications. These companies were categorized based on coverage and market focus as shown in Table 1.

Of the 14 systems, 5 provide regional coverage over the continental United States (CONUS) with similar services for Alaska and Hawaii, 3 are extensions of existing systems, and 6 provide global coverage. The extensions are applications to add satellites to direct broadcast service (DBS) systems with the ability to transmit data at Ka band. Data transmission was listed as a secondary service for these systems, with their main focus being DBS.

The existence of so many different proposed systems to provide broadband communications raised the issue of whether a metric could be constructed to undertake a systems evaluation of such systems. To focus the analysis, five of the worldwide systems were chosen as models for construction of the metric. These systems are Spaceway,[1–3] Astrolink,[4] CyberStar,[5] VoiceSpan,[6] and Teledesic,[7] and a summary of their characteristics from the FCC filings is shown in Table 2.

The concept of cost per function as a metric was developed to compare systems that are technologically very different yet perform a similar function. The comparison that allows the systems to be evaluated on an equal basis is the cost incurred to achieve a particular function. In the case of global cellular communication, it was cost per billable minute.[8,9] For launch vehicles, the metric is cost per kilogram to a given orbit. For broadband communications systems, it is the cost to provide high-speed information transfer.

In the current market, home users of the Internet are typically billed on either a per-minute, connect-time basis or a flat monthly fee for unlimited connect time. Because the majority of home users are limited by the data rate of current modem technology, data transfer rates can be neglected, and a per-minute billing method is convenient for on-line services. However, as a metric for comparison of broadband satellite communications systems, it neglects the capacity differences and varying connection rates present in the systems. A comparative metric of cost per minute at a specific data rate is capable of comparing systems that can provide vastly different connection speeds. The broadband systems being compared will be high-speed data connections ideal for multimedia communication; thus a T carrier level 1 (T1) (1.544 Mbps) data rate was selected as the rate for comparative analysis. T1 connections are considered well suited to high-traffic systems, company-wide systems, wide-area networks, and Web server applications, thus representing the wave of the future for Internet communications ("SelectNet, Inc., an Internet Service Provider," http://www.select.net, April 1996). The cost per T1 minute is the metric used to compare the broadband satellite systems. It is the cost per T1 minute that the company needs to recover from customers to achieve a specific internal rate of return. Once the achievable capacity and system costs are known, the cost per T1 minute can be estimated. The achievable capacity depends on the available market and the satellite system design. System costs include recurring and nonrecurring estimates for satellite design and construction, launch, insurance, gateways, gateway and control center operations, and terrestrial Internet connections.

This paper develops the necessary components for an analysis with the cost per T1 minute metric. First, the target market is analyzed and estimated. Then system capacity is determined through a computer simulation. Finally, the modeled systems are costed and all of these elements are combined to obtain the cost per T1 minute. The modeled systems are then compared based on the cost per T1 minute metric.

## Market Analysis

An understanding of the target market is crucial to appropriate system design. The market is essential to constructing the cost per T1 minute metric and provides a focus for design and implementation strategy. Three different market models are developed to provide estimates of bounds of Internet growth.

By any estimate, the Internet is currently experiencing rapid growth. The inception of the World Wide Web (WWW) has caused a virtual explosion in Internet traffic. Recent surveys estimate that approximately $35 \times 10^6$ to $37 \times 10^6$ people in the United States age 16

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**Table 1 Companies filing with the FCC**

| | |
|---|---|
| CONUS | |
| | Millennium (Motorola) |
| | Echostar |
| | Netsat |
| | Ka-Star |
| | Vision Star |
| Worldwide systems | |
| | Spaceway (Hughes) |
| | Astrolink (Lockheed Martin) |
| | Teledesic (Gates/McCaw) |
| | VoiceSpan (AT&T) |
| | CyberStar (SS/L) |
| | Morning Star |
| Extensions | |
| | GE Americom |
| | PanAmSat |
| | Orion Atlantic |

**Table 2 System summary**

| System | Altitude, km | Operational satellites | Locations (planes) | Access scheme[a] | Spot beams |
|---|---|---|---|---|---|
| Astrolink | 35,785 (GEO) | 9 | 5 | TDMA/FDMA | 192 |
| CyberStar | 35,785 (GEO) | 3 | 3 | FDM/TDMA | 27 |
| Spaceway | 35,785 (GEO) | 8 | 4 | TDMA | 48 |
| Teledesic | 700 (LEO) | 840 | 21 | TDMA/FDMA | 64 |
| VoiceSpan | 35,785 (GEO) | 12 | 7 | CDMA | 32–64 |

[a]TDMA, time-division multiple access; FDMA, frequency division multiple access; FDM, frequency-division multiplexing; CDMA, code division multiple access.

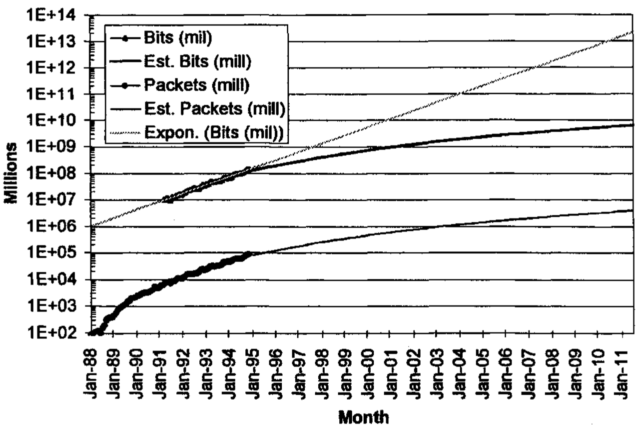


Fig. 1 NSF traffic and projected growth.

and over have access to the Internet ("CommerceNet/Nielsen Internet Demographics Survey," http://www.nielsenmedia.com/commercenet/exec_sum, Oct. 1995). Local Internet service providers are springing up all over the United States, and universal resource locators have become common sights on printed advertising. Corporate America has caught on to the Internet trend and spent \$12.4 $\times$ $10^6$ in the fourth quarter of 1995 to purchase space on Web sites.[10] Clearly, the Internet is growing. Most sources say that the growth is currently exponential; however, those estimates are based on very few data and some intuition. The data that are available come from the old National Science Foundation (NSF) backbone that was administered by Merit, Inc., from its inception in fall of 1987 to its decommission in April 1995. With the decommissioning of the NSFNET and the subsequent privatization of the Internet, collection of data on traffic traversing the entire backbone ceased. Merit gathered data on traffic traversing the NSFNET from January 1988 to April 1995 ["NSFNET Statistics (1988–1995)," http://www.merit.edu/nsfnet/statistics, Oct. 1995]. Depending on the method of examining the data, two very different Internet growth trends can be found. The constructed growth trends and the NSF backbone data in packets from November 1988 to December 1994 and in bytes from January 1991 to December 1994 are shown in Fig. 1.

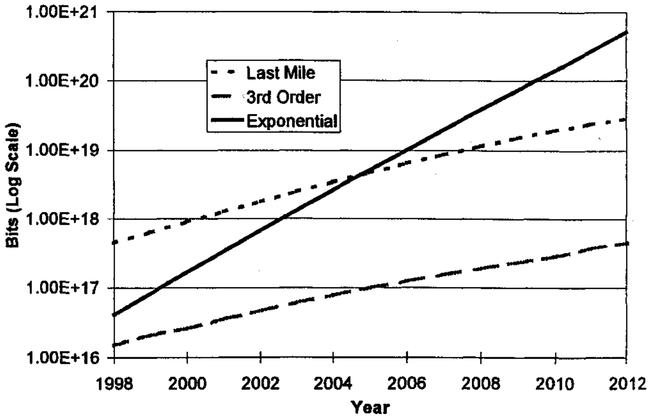


Fig. 2 Market scenarios.

**Exponential Growth Model**

First, the Merit data in terms of the number of packets traversing the NSF backbone from January 1991 to April 1995 were examined. In November 1994, traffic began moving from the NSF backbone to the new network access point (NAP) architecture. The new NAP architecture was a realization that the growing role of commercial service providers needed to be accommodated and would allow the NSF to step back from actually operating a network.[11] The NAP architecture allows regional networks and network service providers to connect and exchange traffic with no content or usage restrictions ("The Chicago NAP," http://nap.aads.net/The_Chicago_NAP.html, May 1996).

The NSF backbone consisted of computers in the United States. Though data entering the NSF backbone could potentially come from networks in other countries, it is assumed that the majority of the data traversing the network at the time the data were taken is primarily from the United States, inasmuch as over half of all Internet hosts are located there (Lottor, M., "Internet Domain Survey, July 1996," http://www.nw.com/zone/WWW/report.html, Aug. 1996). To obtain a projection of the world market, the amount of data traversing the NSF backbone was doubled. Neglecting the data obtained after the transition to the new architecture began, the data are projected forward to the year 2010. An exponential curve, shown in Figs. 1 and 2, that most Internet users expect is obtained. Because of the new architecture, data on bytes traversing the network after April 1995 are not available.

**Third-Order Growth Model**

Looking at the Merit data in terms of the number of packets traversing the NSF backbone from January 1988 to April 1995 yields a very different growth curve. Again, data from December 1994 to April 1995 are neglected due to the transition to the new architecture. During the period prior to the transition, the average packet size was approximately 200 bytes; thus, to transform this packet data into bits, it is assumed that a packet is on average 200 bytes. As with the exponential model, the data are doubled to go from NSF backbone bits to world bits. When these data are projected forward, a third-order curve is obtained. This curve is shown in Figs. 1 and 2.

These market models are assumed to be upper and lower bounds to the growth of Internet traffic. The third-order model is a very conservative estimate due to the assumption of a 200-byte packet. In reality, packets are not a constant size. Thus, assuming a constant-size packet underestimates growth of high-bandwidth services such as the WWW, which did not become the largest source of network traffic until April 1995. With the growth of Internet commerce and the beginnings of Internet telephony, it appears that the third-order market is not a likely scenario. The model is kept to assist in examining the systems when they do not reach capacity saturation. The exponential model is considered an upper bound because the Internet is still in its infancy, and growth rates of technology are typically exponential in the early years and then begin to level off. Also of note is that both of these models discuss the growth of the entire Internet. It is anticipated that some of this traffic will also come from the extension of terrestrial land lines.

**Last Mile**

As another estimate, a market model based on computer growth trends was developed. Computer penetration in various countries is projected to begin to equalize at the country's respective percentage of world gross domestic product (GDP) (Central Intelligence Agency, *The World Factbook 1995*, http://www.odci.gov, Jan. 1996). Such a trend corresponds to current statements that markets such as the United States are beginning to reach saturation and the growth rate is rapidly tapering off.[12] Many products experience high growth rates at their inception that then begin to taper off as the markets that can afford the product reach saturation. As computers are introduced in foreign markets, growth rates are expected to increase rapidly.

Included in the estimate of the growth of personal computers are those computers that are connected to the Internet as hosts. Hosts on the Internet are those computers that have a permanent connection to the Internet. They have Internet protocol (IP) addresses and are listed in the domain name system. A computer that dials in and is dynamically assigned an IP address for the duration of its connection is not considered a host computer. Thus, the last mile market is the difference between the number of computers worldwide and the number of Internet hosts and is shown in Fig. 2.

**Market Summary**

Three different market scenarios were developed to attempt to simulate the potential growth of Internet traffic. As shown in Fig. 2, the third-order and exponential models represent upper and lower bounds to the market development. The last mile model is larger than the exponential initially, but the growth of the exponential model quickly overcomes it and surpasses it by the year 2005. This results from the two different quantities that the models are presenting. The last mile model represents computers not connected to the Internet. The exponential model is a measure of the growth of the Internet itself. These two quantities are intertwined. The Internet is growing, and as the Internet grows the amount of traffic traversing the network and the number of hosts attached to it also increase. Because the Internet is growing faster than the computer market, the increase in the number of hosts means a corresponding decrease in the number of computers not connected. Despite the fact that the exponential and last mile market were constructed from different data, their estimates of growth are fairly similar. On the other hand, the third-order model lies far below the other two.

**Worldwide Distributions**

Once estimates on the growth of the worldwide market are obtained, these markets must be globally distributed. To facilitate this distribution, the world was divided into 5° latitude and longitude grids.

The common measures for purchasing power are based on the wealth of countries as a whole or on the wealth of individuals; thus, the world market was distributed to countries in two different ways: GDP and GDP per capita. Distributing the world traffic from country to country according to a country's percentage of the world GDP accounts for the country's purchasing power as a whole, regardless of population. On the other hand, distributing the world traffic according to GDP per capita accounts for the purchasing power of an individual within a country when the country's wealth is evenly distributed among the population. In a GDP per capita distribution, countries with large populations are penalized. Even if the country as a whole appears wealthy with respect to other nations, distributed on a per individual basis, the amount of wealth per person is small. For example, in a scenario where a simplified country consists of three individuals, one with enough money to buy a computer and two with barely enough money to sustain themselves, the distribution used to determine the number of computers in the country plays an important role. In a GDP distribution, the country would be allocated one computer, because the total wealth of the country is enough to afford one. However, in a GDP per capita distribution, the country would be allocated nothing, because the one individual's wealth distributed among three people is not enough to afford a computer.

Once various percentages of the market are allocated to a country, the data are further distributed according to the population distribution within the country. A more highly populated area of a country is expected to contribute a larger portion of that country's Internet traffic than a lower-density-population area. In this manner each of the three markets is distributed according to GDP and GDP per capita, giving a total of six market scenarios to be examined.

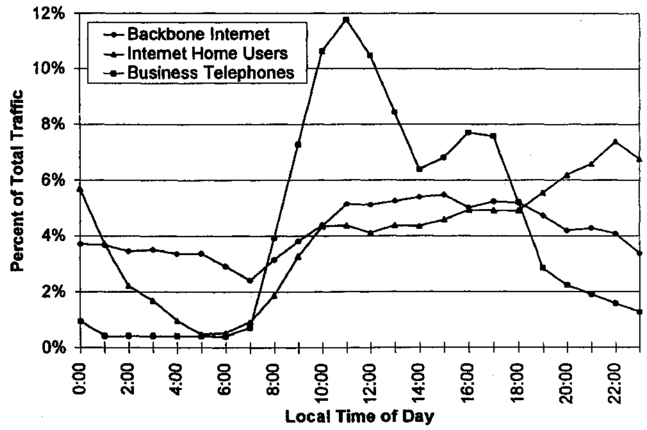


**Fig. 3 Time of day distributions.**

**User Profiles**

To determine whether a time of day distribution needs to be taken into account for the market data, the behavior of the potential users of the systems is examined. The users can be divided into three different categories: home users, business users, and backbone users. Home users of the service are individuals who desire Internet access for things such as e-mail and entertainment, similar to users found on America Online, Netcom, or Algonet, an Internet service provider located in Sweden. Business users are those users that use the service to either telecommute or connect from a place of work. Backbone users would be similar to corporate intranets or actual national and regional backbones that need to be able to communicate at high-data rates. These groups exhibit very different behavior patterns, as shown in Fig. 3.

Examining data obtained from Algonet, the highest usage periods for home users, with a peak of around 7% of daily users logged in, occur between the hours of 8 p.m. and 11 p.m. local time with a large decline at midnight. The number of users reaches a low at around 6 a.m. local time, and local minimums occur at noon and 6 p.m. This behavior pattern is not surprising for people that use the system after they get home from work or school and then log out when they eat and sleep.

For telecommuters and other business users of the Internet, traffic patterns are expected to be similar to those of phone calls for a business. Activity reaches a peak of about 12% at 10 a.m. and is highest from the hours of 8 a.m. to 4 p.m. local time. After 4 p.m., usage tapers off until midnight, when it reaches nearly zero. The peak usage period for a business occurs 12 h prior to the peak for the home user and is slightly greater in magnitude.

Data on backbone Internet traffic were downloaded from NORDUnet, a backbone network based in Denmark ("NORDUnet Maps and Statistics," http://nic.nordu.net, Dec. 1995). Traffic for data on all of NORDUnet's lines has a very different time of day distribution from that of home and business users. The traffic on a backbone has much smaller fluctuations than business and home user traffic examined individually. The reason no large fluctuations exist in a backbone time of day distribution is that a backbone sends and receives data from computers worldwide and requests from different time zones average out into a nearly constant flow of traffic.

Thus the actual time of day distribution for any of the satellite systems would depend heavily on marketing strategies. By varying what kind of user the services are marketed to, the systems have the ability to construct almost any time of day distribution they desire. Time of day distribution is, therefore, neglected in the capacity simulations.

## Capacity Simulations

An unbiased evaluation of the cost per T1 minute metric requires an estimation of the achievable capacity of the satellite communication system. The achievable capacity is defined as the total number of

Table 3 System parameters

| System | Number of satellites | Orbit | Satellite capacity, Gbps |
|---|---|---|---|
| GEO(9/192) | 9 | GEO | 7.7 |
| GEO(3/27) | 3 | GEO | 4.9 |
| GEO(8/48) | 8 | GEO | 4.6 |
| LEO | 840 | LEO | 13.3 |
| GEO(12/64) | 12 | GEO | 5.9 |

bits that the system can realistically transfer at a given instant of time. [Strictly, for a true system, the achievable capacity would change in time. However, within our assumed market models, there is no significant time of day distribution. Consequently, the achievable capacity is assumed constant throughout the day. This assumption is easily justified for the geosynchronous-Earth-orbit (GEO) systems but is a little more complicated for a low-Earth-orbit (LEO) system.] The achievable capacity differs from the theoretical capacity (defined as the sum total of all transponder capacities in the system) because of the limiting effects of market demographics, capture and exhaustion, rain attenuation, interchannel interference, beam overlap, and limited payload power resources.

To correctly estimate the quantitative effects of these factors, a computer simulation was written to model operation of a broadband communication satellite system within a realistic market scenario. VoiceSpan, Astrolink, Spaceway, CyberStar, and Teledesic were used as models for the GEO(12/64), GEO(9/192), GEO(8/48), GEO(3/27), and LEO constellations used in the simulation. The notation represents the orbit, number of satellites, and number of spot beams per satellite for each modeled system. The basic system parameters are listed in Table 3.

### Logic Flow

The simulation calculates the number of bits that can be transferred through a given satellite broadband-communication system under the constraints of a distributed market model, achievable link margins, rain attenuation, and limited satellite power resources. The program can simulate both LEO and GEO satellite systems with no modifications. Intersatellite links can be included in simulations if required.

The overall premise of the simulation is to project spot beams onto the Earth from the satellite positions given by ephemeris data. The spot beams have beamwidths corresponding to the gains given in a system definition file. The simulation calculates a link budget for each channel (in each beam) and estimates the likely rain attenuation based on a global distributed rain model. Based on the attenuation and resulting link margin, the availability of the link is calculated. This percentage availability is multiplied by the transponder capacity to obtain the maximum billable data rate for that channel, achievable only where the local market can support such a capacity. The accessible market for each beam depends on the coverage area and on the magnitude of the market locally. The realistically achievable capacity for each channel is the minimum of the supportable data rate and the available market to which it has access. This logic procedure is illustrated as a first-level flowchart in Fig. 4.

### Simulation Results

The computer program was used to simulate operation of the modeled satellite systems. Each system was simulated with the exponential, the third-order, and the last mile market growth models, for both a GDP and GDP per capita distribution, over the expected system lifetimes. To normalize the systems for comparison, deployment of all systems is assumed to begin in the year 2000.

### Intersatellite Links and Achievable Capacity

Intersatellite links are simulated by allocating a certain percentage of the total uplink bits to outgoing traffic. This is equivalent to varying the demand for interregional traffic. To determine the effects on the achievable system capacity of incorporating intersatellite links, GEO(3/27) was simulated with two interregional crosslinks per satellite with various percentages of the total uplink bits being

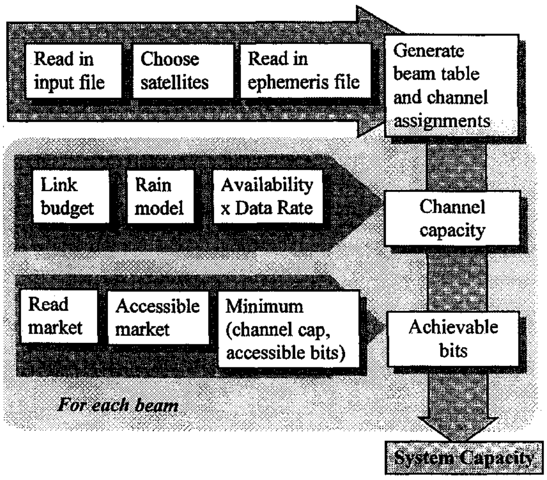


Fig. 4 Level 1 flowchart.

routed to the crosslinks. The crosslink data capacity was taken to be 1 Gbps.

The intersatellite links have no noticeable effect on the calculated achievable capacity. This will be true provided the data throughput capability of the crosslinks is sufficient to carry the interregional demand. If, however, the crosslink capacity is too small, the achievable capacity will be reduced slightly as the interregional traffic will be limited. There is no conceivable way for intersatellite links to increase the achievable system capacity under the assumed market models; all of the bits must eventually be downlinked and are then constrained by the locally supportable market or by downlink capacity limitations. Their presence makes little or no difference to the achievable system capacity, and so crosslinks were omitted in the simulations.

### GEO(3/27) Capacity Results

GEO(3/27) was simulated for the different market scenarios over its expected lifetime. The years of the simulation ran from 2000 to 2010. The exponential and last mile market models result in similar achievable capacity profiles, whereas the third-order market models give greatly reduced capacities.

Initially the system capacity is small over all of the market models, with only the North American market being accessed, and there are few or no differences between the different distributions at this time. The GDP per capita distribution begins to deviate from the basic GDP distribution with the launch of the third satellite in 2003. This is due to the population demographics in Asia, which differ greatly from that of Europe and America. In the latter two continents, the most powerful commercial countries also have the largest populations (United States, Germany, and United Kingdom). In Asia, however, there are both large, poor countries (China) and small, wealthy countries (Singapore). Consequently, the achievable capacity using markets based on a per capita distribution differs from the basic (GDP) results most markedly in Asia. Generally, the per capita distributions result in marginally lower capacities.

The last mile markets give the largest capacity during the early years. During the deployment period, the achievable capacity of the system increases rapidly for this last mile market scenario. By the time the total complement of satellites has been launched in 2003, the achievable capacity of the system has begun to approach the saturated design capacity. The system has a slower increase in capacity under the exponential model, approaching saturation later, in 2005. For the third-order model, the system never reaches saturation.

### GEO(8/48) Capacity Results

GEO(8/48) was simulated for the different market scenarios over its expected lifetime. The years of the simulation ran from 2000 to 2010. There is little or no variation between the two alternate distributions for any of the three market growth models. This differs from the GEO(3/27) capacity profiles, which showed noticeable deviations between the two market distributions. GEO(8/48) is insensitive to the market distribution because of the comprehensive global coverage of the spot beams. GEO(8/48) has access to almost all of the world's potential markets. The distribution of those markets, therefore, has a small impact on the total system capacity.

Once all satellite resources are on orbit by 2003, the achievable capacity closely follows the maturation curve of the markets, until system saturation occurs. The last mile market gives the largest capacity during the early years (2000–2003) and increases steadily toward saturation in 2008. The system capacity for the exponential market increases in a correspondingly exponential way through the middle period of the simulation (2002–2005) and reaches saturation around 2007. The capacity for the third-order market model increases at the same rate as the market growth and never saturates.

#### LEO Capacity Results

The LEO constellation was simulated for the different market scenarios over its expected 10-year lifetime from 2000 to 2010. There are no discernible differences between the two alternate market distributions for any of the growth models. The lack of variation is a result of the almost uniform coverage characteristic of the LEO system, which allows all of the market to be accessed, wherever it is located.

None of the capacity profiles shows saturation. Over the entire lifetime of the system, the system has a larger link capacity than the global market can support. The last mile market gives the largest achievable capacity until 2005. The capacity for the exponential market is the largest after 2005. The third-order growth model gives the smallest capacity, almost two orders of magnitude less than the exponential market capacity in 2010. The implication of these trends is that, at least for the broadband market, the LEO system is overdesigned.

#### GEO(9/192) Capacity Results

GEO(9/192) was simulated for the different market scenarios over its expected lifetime. The years of the simulation ran from 2000 to 2010. Unlike the GEO(8/48) constellation, GEO(9/192) shows marked differences in the capacity attainable for the different market distributions. The difference between the achievable capacity for the GDP and GDP per capita distributions is due to the beam patterns that it employs. Rather than concentrating its beams on the most heavily populated and industrialized areas, GEO(9/192) spreads its beams evenly over the land masses. Thus, in the GDP per capita market models where traffic is more concentrated in specific regions, the beams quickly saturate, and the beams in other regions are underutilized.

The early deployment of the constellation and the widely distributed spot beams cause the individual satellites to not reach saturation as they are deployed. Because a majority of GEO(9/192)'s spot beams are underutilized, the achievable capacity follows the market maturation. In the exponential models, saturation occurs in the year 2010; the other models never reach saturation due to the more concentrated nature of the traffic in those models.

#### GEO(12/64) Capacity Results

GEO(12/64) was simulated for the different market scenarios over its expected lifetime. The years of the simulation ran from 2000 to 2010. Like the GEO(8/48) and GEO(3/27) constellations, GEO(12/64)'s beam patterns are highly concentrated in developed areas with large populations. Of note is that GEO(12/64) has a total system capacity nearly identical to that of GEO(9/192), yet due to the difference in beam patterns, there is far less of a difference in achievable capacity between market distributions.

As was seen with the GEO(9/192) data, GEO(12/64) saturates in the exponential market in the year 2010. Though its yearly capacities in all models are larger than GEO(9/192)'s, GEO(12/64) is still overdesigned for the market that it can reach, and the achievable capacity simply tracks market growth.

## System Costs

Estimating the cost of the system is critical to the calculation of the cost per T1 minute. The total cost of the system $C_T$ includes recurring $R$ and nonrecurring $NR$ estimates for satellite design and construction, launch, insurance, gateways, gateway and control center operations, and terrestrial Internet connections. These are given by

$$C_T = NR_{\text{satellite}} + R_{\text{satellite}} + R_{\text{launch}} + R_{\text{insurance}} + NR_{\text{gateway}} + R_{\text{gateway}} + R_{\text{operations}} + NR_{\text{internet}} + R_{\text{internet}} \quad (1)$$

All satellites are assumed to have a lifetime through the year 2010, giving a satellite lifetime of 10 years for the GEO systems and 7 years for the LEO system.

#### Cost Estimation Tools

Several cost estimation techniques are common throughout the cost model. The model works in constant fiscal year 1996 dollars (FY 96 $); thus, all costs are adjusted using the Office of the Secretary of Defense estimates.[13] Cost estimates in constant year dollars are useful for comparing alternatives and simplify computations because interest is assumed to be zero for the period of the estimates.

Also important to the cost model is the spreading of costs over the development period. For the cost model, a 50% development cycle is assumed for all systems. To spread the cost over time, a spreading method that approximates the experience of actual programs was developed by Wynholds and Skratt.[14] For a 50% expenditure at development midpoint, the function becomes

$$F(T) = [10 + T(6T - 15)]T^3 \quad (2)$$

The final technique employed is the use of a learning curve for development. A learning curve describes the relationship between a firm's cumulative output and the amount of inputs needed to produce a unit of output.[15] It accounts for productivity improvements as a larger number of units are produced. The total production costs $C_{\text{prod}}$ for $N$ units is given by

$$C_{\text{prod}} = \text{TFU} \times L \quad (3)$$

where

$$L \equiv N^B, \qquad B \equiv 1 - \frac{\ln[(100\%)/S]}{\ln 2}$$

The learning curve slope $S$ represents the percentage reduction in total cost when the number of production units is doubled. In the cost model, the slopes assumed were 95% for fewer than 10 units, 90% for between 10 and 50 units, and 85% for over 50 units. All satellites are expected to have an operational lifetime of 10 years.

Costs for the satellite system are broken down into recurring and nonrecurring costs. Nonrecurring costs are associated with design, development, manufacture, and testing of the qualification model. Recurring costs include all manufacturing, integration with the launch vehicle, and launch.

#### Space Segment

To estimate the cost of the satellites, a dry mass model of $77,000/kg of spacecraft dry mass for the recurring costs is assumed. The cost per kilogram of dry mass is based on industry experience from communications satellites.[16] The LEO system is assumed to have a nonrecurring cost of seven times the theoretical first unit cost FY 96 $ (TFU) because it is based on new satellite designs and will use mass manufacturing techniques, which require a larger initial investment. Nonrecurring costs for the GEO systems are assumed to be three times the first unit cost because the systems are similar to previous satellite designs and will employ traditional satellite manufacturing methods. The LEO system will likely employ mass manufacturing techniques to produce such a large number of satellites, which will result in economies of scale. For the purposes of comparison, the LEO system is estimated using traditional cost estimates; any implementation of mass manufacturing techniques will simply result in a lower total system cost:

$$\text{TFU} = \$77{,}000 \times \text{dry mass}, \qquad NR_{\text{GEO}} = 3\,\text{TFU}, \qquad NR_{\text{LEO}} = 7\,\text{TFU} \quad (4)$$

**Table 4 Satellite costs, $77,000 model**

| System | FY 96 billion $ |
|---|---|
| GEO(12/64) | 2.7 |
| GEO(9/192) | 1.8 |
| GEO(3/27) | 0.96 |
| GEO(8/48) | 1.3 |
| LEO | 10.7 |

Table 4 shows the recurring and nonrecurring costs of satellite development and manufacture obtained from the $77,000 model. The $77,000 estimate is used as a method to compare relative costs and does not allow the cost of the spacecraft to dominate the other system costs. The methodology of the metric and the relative comparisons are the critical aspects to be considered, and the reader is invited to apply this methodology to an analysis employing alternate figures.

Along with the cost of the satellite construction, there is the cost of launching the satellites to their respective orbits. A cost per kilogram of wet mass to an orbit was calculated for use in the cost model. Cost per kilogram to geosynchronous orbit is $30,530 (FY 96 $). The cost per kilogram to LEO for a near polar inclination such as the LEO constellation's orbit is $15,480 (Ref. 17). To obtain a total launch cost, the wet mass of each satellite was multiplied by its respective cost per kilogram to orbit.

Insurance is a significant portion of launch costs. The insurance on a launch was calculated using a 20% rate on the sum of the recurring satellite and launch cost. This would cover replacement costs for the satellites and the launch vehicle in the event of a launch failure:

$$C_{\text{ins}} = 0.2(R_{\text{satellite}} + R_{\text{launch}}) \qquad (5)$$

**Ground Segment**

The ground segment costs include the costs of gateways to communicate to the satellites, hardware to connect to the terrestrial Internet, a control center to control the satellites, and personnel to operate them. The cost of construction of control centers was not estimated.

For the model, two communications gateways per region of coverage were assumed. It is assumed that each gateway was capable of communication with the terrestrial network and telemetry, tracking, and control. Each gateway requires two Ka-band stationary antennas. Even in the case of the LEO system, the ground antennas will not be tracking the satellite because the satellite tracks specific areas on the ground. The estimated cost for a gateway with antennas and related hardware is $\$15 \times 10^6$ (FY 96 $). The learning curve described earlier is applied to the production of the gateways. A nonrecurring factor of five times the cost of the first ground station is assumed.

Operations costs are estimated by assuming four 5-person shifts for each gateway site and four 12-person shifts for the control center. The estimated cost to support one person is $150,000 per year.[18]

To determine the number of optical carrier level 3 (OC-3) (155 Mbps) circuits necessary per satellite, it was assumed that all of the bits uplinked by the satellite would have to be downlinked to the same region. This would be the case if the satellite system had no intersatellite links to transport traffic. The number of OC-3 circuits is allowed to increase as the number of bits uplinked by the satellite increases with the growth of the market; thus, the total cost of hardware to connect to the terrestrial Internet varies from year to year. The current cost of an OC-3 connection involves both an installation charge, the cost of the hardware, and a recurring cost for maintenance of the connection and agreements required to transport Internet traffic. The installation cost of an OC-3 circuit is estimated at $8500 and the recurring cost at $94,800 per year, all in fiscal year 1996 dollars.

## Cost per T1 Minute

Before the cost per T1 minute metric can be calculated for the example systems, the concept of internal rate of return must be discussed. The internal rate of return of a project is a measure of profitability that takes into account the variation in value of money with time. For a project with the time span and risks similar to those associated with the broadband communications systems, a potential investor would typically require a 30% rate of return. Thus, 30% is the discount rate for which net costs equal net benefits.

The benefits for each year are the amount that would have to be charged to the customer for a T1 link for 1 min times the number of T1 connections available. The customer cost per T1 minute employed includes system costs and a 30% internal rate of return but does not include items such as sales and advertising costs. Using this information to solve for the cost per T1 minute gives the net present value of the system costs divided by the equivalent of the net present value of the number of T1 links available.

**100% Market Availability**

Assembling the capacities and the cost estimates, the cost per T1 minute can now be calculated for the modeled systems. The systems were each given access to 100% of the available market on the ground; thus the results shown in Fig. 5 assume that only one system exists at any given time. As shown, for all of the market models except the third-order growth model, the cost per T1 minute is similar. In the third-order model, the cost per T1 minute is significantly larger because there is not enough market available to allow the systems to reach saturation. The systems are overdesigned for the available market and, thus, the total system cost must be amortized over a smaller number of bits, resulting in the higher cost per T1 minute. Because the third-order market model is a low estimate of Internet growth, it will be neglected in favor of closer examination of the remaining market models.

Closer examination of the remaining market models (shown in Fig. 6) reveals that there is very little difference in the cost per T1 minute among the systems. There is also only a marginal difference caused by the distribution of the market by GDP or by GDP per capita. In the last mile model, the LEO system is still overdesigned for the market that is available, resulting in a higher cost per T1 minute. Thus, the metric allows a baseline comparison of different

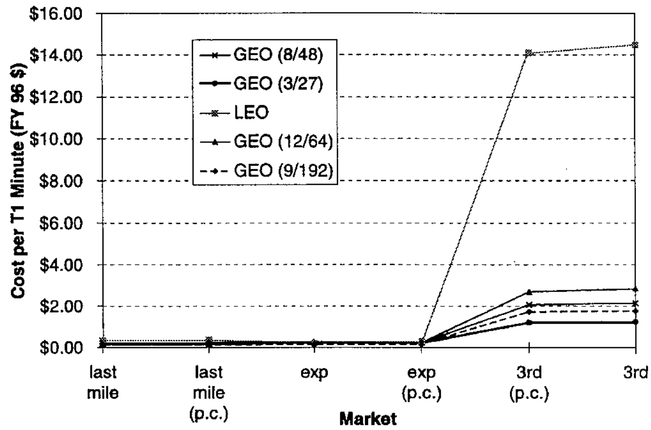


Fig. 5 Cost per T1 minute, all markets, 100% market availability.

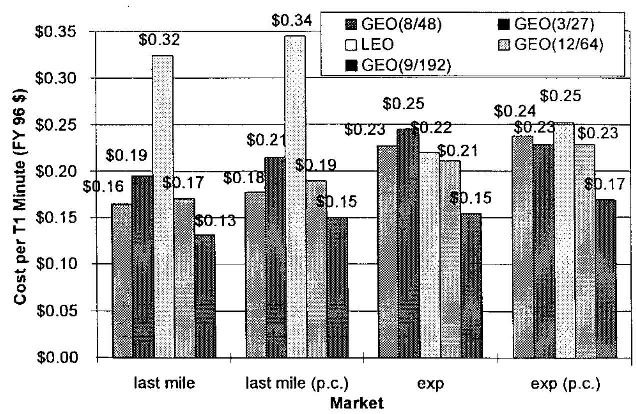


Fig. 6 Cost per T1 minute, 100% market capture.

Table 5 Market availability

| Year | GEO(3/27) capture, % | GEO(8/48) capture, % | Available to LEO, % |
|---|---|---|---|
| 2002 | 11.31 | 17.86 | 70.83 |
| 2003 | 10.86 | 16.02 | 73.12 |
| 2004 | 8.68 | 14.02 | 77.30 |
| 2005 | 6.90 | 12.11 | 81.12 |
| 2006 | 5.23 | 10.24 | 84.53 |
| 2007 | 4.12 | 8.64 | 87.24 |
| 2008 | 3.27 | 7.17 | 89.57 |
| 2009 | 2.61 | 5.89 | 91.50 |
| 2010 | 2.14 | 4.87 | 92.99 |

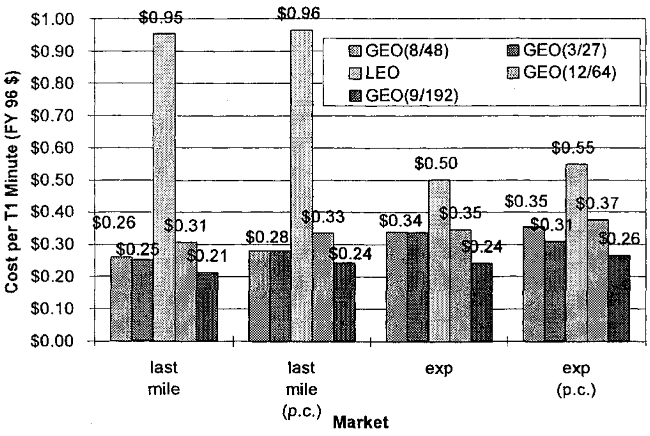


Fig. 7 Cost per T1 minute, 30% market availability.

systems designed to provide a similar service and also a preliminary determination of the type of market growth that is necessary for a system to be viable. Also of note is that the LEO system is competitive with the GEO systems in large markets. Inclusion of cost reductions due to mass manufacturing would only further reduce the cost per T1 minute for the LEO system.

### 30% Market Availability

To explore the use of the metric in a more competitive scenario, assume three systems competing equally for customers. Each system was allowed to access only 30% of the available market. The cost per T1 minute spread shown in Fig. 7 results. As expected, the LEO system's cost per T1 minute increases dramatically in the last mile market. The system was overdesigned for 100% market capture in that market; thus, the decrease in market availability only exacerbates that condition.

### Competitive Market

Whereas allowing the systems to have access to only 30% of the total market is illustrative in showing sensitivity to market capture, it does not represent a true competitive environment. Restricting each system to 30% of the market gives smaller systems an advantage because the larger systems would not be able to access the market remaining when a smaller system reaches saturation. In reality, the systems will be competing with one another for customers. Smaller systems such as GEO(3/27) will reach a capacity limit even when only being allowed 30% of the market. Any market remaining will be available to the other systems and contribute to a larger customer base and, thus, a decrease in cost per T1 minute. As an example, consider a combination of three systems reaching operation, the GEO(8/48), GEO(3/27), and LEO systems. Examining this situation for the last mile per capita market for the years in which the LEO system will be operational yields the results shown in Table 5.

As shown in Table 5, even in the market in which LEO's cost per T1 minute sees its largest increase, the actual market that will be available to the system is greater than 60%. GEO(8/48) and GEO(3/27) are able to capture less than the 30% of the market allocated to them due to the location of their spot beams. Because of a combination of the market distribution and spot beam locations, there are portions of the world market that the GEO(3/27) and

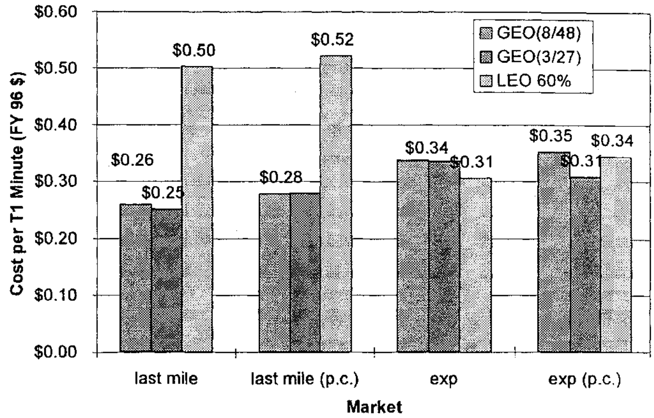


Fig. 8 Cost per T1 minute, LEO 60% market availability.

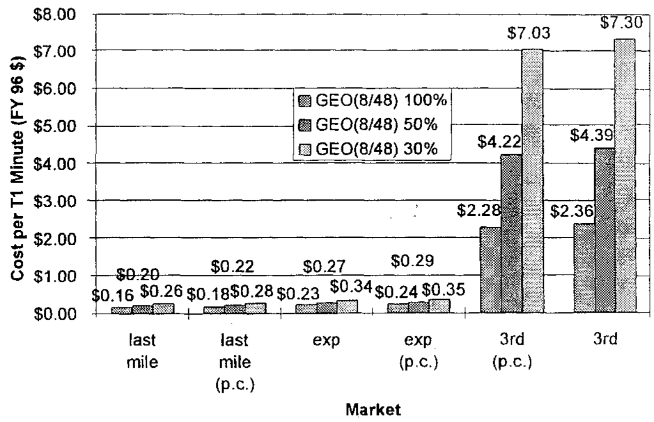


Fig. 9 Effect of market capture on GEO(8/48).

GEO(8/48) systems cannot access. The LEO constellation, with complete global coverage, has the technological capability of capturing the leftover market regardless of where globally the market is distributed. This will significantly decrease its cost per T1 minute. Figure 8 shows the cost per T1 minute obtained when the LEO system is given access to 60% of the market and GEO(3/27) and GEO(8/48) are held to 30%.

Because the LEO system's capacity is large, increasing the amount of market it has access to results in a direct reduction of the cost per T1 minute. As shown in Fig. 8, the cost per T1 minute drops significantly if the LEO system is allowed access to the majority of the market remaining after the GEO(8/48) and GEO(3/27) constellations reach saturation.

From this example, it can be seen that the metric can be used to determine the market bounds for financial viability of the system. As the system gets farther from saturation, the cost per T1 minute experiences much larger variations with changes in the available market.

### Market Capture

For the GEO systems, changes in market capture have the largest effect on the cost per T1 minute in markets where the system does not reach saturation. Figure 9 is a more detailed examination of the effects of market capture on the GEO(8/48) constellation. The scenarios depicted are 100, 50, and 30% market capture. The large differences in the cost per T1 minute seen in the third-order scenario further illustrate the importance of ensuring that the system is not overdesigned for the anticipated market.

### Delayed Deployment

The metric can also be employed to help determine an optimal deployment strategy. Examining GEO(8/48) allows sufficient possibilities that a few restrictions are placed on the deployment schedule for the example. For the purposes of example, global operating capability is assumed to occur by the year 2000. The final satellites

**Table 6 Eight-satellite constellation, delayed deployments**

| Strategy | Year 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|
| Nominal | U.S. 1/Europe 1 | South America 1/Asia 1<br>U.S. 2/Europe 2 | South America 2/Asia 2 | | | |
| 1 | U.S. 1/Europe 1 | South America 1/Asia 1 | U.S. 2/Asia 2 | | | South America 2/Europe 2 |
| 2 | U.S. 1/Europe 1 | South America 1/Asia 1 | | U.S. 2/Asia 2 | | South America 2/Europe 2 |
| 3 | U.S. 1/Europe 1 | South America 1/Asia 1 | | | U.S. 2/Asia 2 | South America 2/Europe 2 |

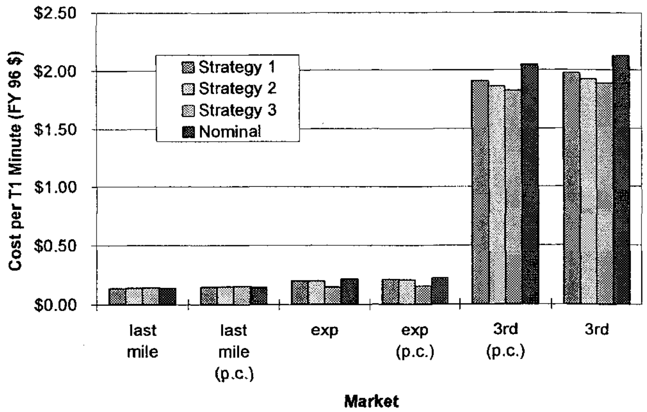


Fig. 10 Variation in time of launch, all markets, GEO(8/48).

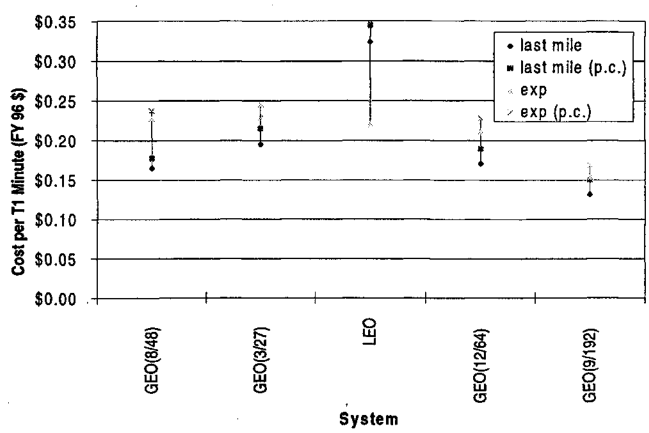


Fig. 12 Cost per T1 minute, all markets, all systems.

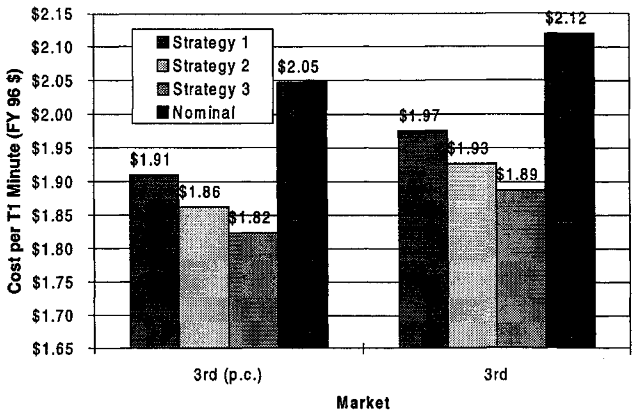


Fig. 11 Variation in time of launch, third-order market, GEO(8/48).

are assumed to be launched and become operational by 2003. These restrictions allow the deployment schedule of six of the satellites to be fixed and two to vary, as shown in Table 6. For this example, it is assumed that those two satellites will be launched in the same year and that year is allowed to vary. When the deployment schedules are used to calculate the cost per T1 minute, Fig. 10 results.

From Fig. 10, it appears that delaying the launch of the two satellites has very little effect in markets where the satellite system has reached capacity saturation. However, in underdeveloped markets such as the third-order scenario, the decrease in cost due to the drop in net present value obtained by delaying the launch of the satellites has a significant effect on the cost per T1 minute. Figure 11 provides a closer examination of the cost per T1 minute differences between the strategies in the third-order market. Thus, if the Internet market does not develop as rapidly as expected, delaying the launch of additional satellites is beneficial. Because delayed launch does not have a significant effect on markets that develop more rapidly and GEO(8/48) is not significantly affected by market capture in those scenarios, delaying the launch of additional satellites until the market has had a chance to mature is an option to be considered.

Figure 12 shows a summary of all of the systems examined across the more likely last mile and exponential market scenarios. It can be seen that systems such as GEO(3/27) that are designed to focus on the heaviest market regions have the least variation in cost per T1 minute across markets. Thus, with the help of the metric, a deployment and beam placement strategy can be designed to make the system adaptable to variations in the market.

## Conclusions

A cost per T1 minute metric was developed and used to compare 12-, 9-, 8-, and 3-satellite GEO systems and a LEO system. Three different market models were developed and geographically distributed according to GDP and GDP per capita. The systems were simulated to determine achievable capacity, taking into account limitations including market penetration, satellite power, beam overlap, and link availability. Life-cycle costs were estimated for satellites, launch, launch insurance, gateways, Internet connection hardware, and gateway and control center operations. The achievable capacity and cost estimates were utilized to calculate a cost per T1 minute with a 30% internal rate of return.

Evaluation of the modeled systems using the metric showed the usefulness of the metric in the design and deployment process. The metric can be used to aid in the placement of spot beams, as illustrated by the differences in the value of the metric for the GEO(9/192) and GEO(12/64) systems. The system capacities are nearly identical; however, the GEO(9/192) system is much less sensitive to market variations due to the uniform distribution of its spot beams. The metric also served to show that a deployment strategy can significantly decrease a system's sensitivity to variations in market development, as shown by the example strategies for the GEO(8/48) constellation. Minimizing sensitivity to market variation is a critical issue, due to the uncertainty inherent in attempting to predict the growth of future markets. The cost per T1 minute metric is a useful tool for the design process and the minimization of risk.


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