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Cost per Billable Minute Metric for Comparing Satellite Systems

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The cost per billable minute is the metric to compare the efficiency of different mobile satellite system architectures. The cost per billable minute to achieve a specified rate of return is determined from estimates of the useful system capacity and life cycle costs. To evaluate the useful system capacity, a computer simulation was developed to model the complex interaction between satellites, gateways, capacity limits, and an expected market model. The major capacity limiting factors addressed include frequency reuse, constellation design, link availability, spotbeam patterns, multiple access schemes, and satellite power. The life cycle costs were estimated for the satellites, launch vehicles, gateways, public switched telephone network hardware connections, operations, and launch insurance. The metric is evaluated for six model systems in low, medium, and geostationary Earth orbits to demonstrate the usefulness of the metric in the design process.

Nomenclature

B = bandwidth, Hz
C = uplink signal, W
d = discount rate
E_b = energy per bit, W/bit
F = fraction of cost consumed
G_r = antenna receive gain
G_t = antenna transmit gain
g_p = power control margin, W
I_{self} = self-interference noise density, W/Hz
k = Boltzmann's constant, 1.3806×10^{-23} W/Hz-K
L_b = blockage and fading losses
L_c = circuit loss
L_p = average atmospheric propagation losses
L_s = free space loss
M = link margin
M_{dry} = satellite dry mass, kg
m = equivalent number of users contributing interference power from other spotbeams and frequency bands
N = number of production units
N_B = number of spotbeams
N_I = number of interfering users
N_u = number of users in spotbeam
N_0 = noise density, W/Hz
n = total number of years
P_{avg} = average transmit power, W
P_{ch} = total transmit power, W
P_{peak} = peak transmit power, W
P_{rf} = maximum payload downlink rf power, W
R = voice data rate, bps
S = slant range, m
S_L = learning curve slope
T_f = fraction of total time elapsed
T_{sys} = system noise temperature, K
T_1 = theoretical first unit cost, dollars fiscal year 1994 ($FY94)
V_a = voice activity factor
x_i = cash flow for year I ($FY94)
α = interference factor
$\varepsilon_{\text{dc to rf}}$ = dc to rf power conversion efficiency factor

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Introduction

SINCE 1990, many organizations have proposed a new generation of worldwide mobile voice satellite services using transceivers about the size of today's handheld cellular phones. Systems have been proposed using satellites in geostationary Earth orbit (GEO), medium Earth orbit (MEO), highly elliptical Earth orbit (HEO), and low Earth orbit (LEO) requiring 3–66 operational satellites. All of the systems will utilize multiple spotbeams and different combinations of code-division multiple access (CDMA), time-division multiple access (TDMA), and frequency-division multiple access (FDMA) schemes. Table 1 lists some of the defining characteristics for a number of these proposed systems.

Many studies have been completed in the last five years addressing the perceived benefits and limitations of the various proposed architectures. These studies range from general surveys to detailed technical comparisons between system architectures. Some of the largest and most detailed studies, conducted by the MITRE Corporation, examine the merits of many of the systems and other important factors that will influence the success of the proposed systems.[1–3] The debate over which type of system will best satisfy the expected market involves many different aspects of the system design, and the answers are not inherently obvious. In the end, the effectiveness of each design approach will be measured by how cost effectively each system is able to satisfy the expected market. Traditionally, fixed service communications have been performed by satellites in geostationary orbits using fixed, wideband transponders. As the capacity of these systems was marketed on the basis of leasing these transponders, a common metric used to evaluate geostationary communication satellites was the on-orbit cost per transponder year.[4] This metric provided both a direct relationship between system cost and performance and a meaningful way to evaluate the cost effectiveness of competing designs. Mobile communication satellite systems, which will be marketed on the basis of a single voice circuit, should be evaluated based on the cost per billable minute. This paper proposes a methodology of comparing satellite systems using a cost per billable minute metric.

The cost per billable minute is what a company needs to recuperate from customers through monthly service fees, per minute charges, handset sales, and other revenue sources to achieve a given rate of return. The internal rate of return is a measure of profitability that represents how much of a return can be anticipated from an investment. Providing all else is equal, the system achieving the lowest cost per billable minute will be the most cost competitive and profitable. The cost per billable minute can be estimated from the system's useful capacity and its total cost over the system lifetime. The useful system capacity, measured in billable minutes, depends on the available market and the mobile satellite system design. Life cycle costs include development and operations costs

Table 1 Summary of proposed systems

System	Altitude, km	Operational satellites	Orbital planes	Multiple scheme	Number of spot beams
Iridium[a]	768–787 (LEO)	66	6	FDMA/TDMA	48
Globalstar[a]	1,414 (LEO)	48	8	FDMA/CDMA	16
Constellation	2,000 (LEO)	46	8	FDMA/CDMA	32
Ellipso[a]	8,035 (MEO)	7	1	FDMA/CDMA	37
	~674–7,514 (HEO)	10	2	FDMA/CDMA	37
Odyssey[a]	10,355 (MEO)	12	3	FDMA/CDMA	61
Iris[a]	10,355 (MEO)	12	3	FDMA/CDMA	48
ICO	10,355 (MEO)	10	2	FDMA/CDMA	163
AMSC	10,355 (MEO)	10	2	FDMA/CDMA	56
Tritium[a]	35,785 (GEO)	3	1	CDMA	~160

[a]Used as a template for modeled systems.

for the satellites, launch vehicles, insurance, gateways, and public switch telephone network (PSTN) connections. In addition to providing a brief description of the model systems used for the study, the following sections will describe a mobile satellite market model, the methodology for simulating the capacity of the system, and the cost estimates used to determine the cost per billable minute metric.

Model Systems

Instead of attempting to directly compare the proposed systems, this paper will concentrate on developing the methodology and tools necessary to evaluate the cost per billable minute metric. To demonstrate the utility of the metric, six model systems are evaluated. As indicated in Table 1, the six model systems are similar to several proposed systems, but because all of the design and cost information required to fairly compare the proposed systems is not openly available to the public, many assumptions are made. The results apply to the model systems and do not reflect the actual proposed systems. The model systems are referred to by their orbit, number of operational satellites, and spotbeams per satellite (LEO66/48, LEO48/16, HEO17/37, MEO12/48, MEO12/61, and GEO3/160). The following set of requirements were used to ensure a fair comparison between the different model architectures: 1) 12-year operational life cycle, 2) 10^{-3} bit error rate (BER), 3) 4800 bps full duplex voice circuit, 4) 0-dB (1) transmit and receive handheld antenna gain, 5) 0.5-W maximum average handset rf transmit power, 6) 1-dB (1.26) average rain and polarization propagation loss for mobile uplink and downlink, 7) 1.5-dB (1.41) total circuit loss for mobile uplink and downlink, 8) 2-dB (1.58) average power control margin, and 9) 294.6 K (21.45°C) handheld system temperature.

Market Study

The potential market distribution and size is an important factor in determining the cost per billable minute. Most of the market information was obtained through guest lectures in Massachusetts Institute of Technology's 16.89 Systems Engineering class during the spring of 1995 (Refs. 5 and 6). The market model is partially based on detailed market research conducted by Peat Marwick's advanced technologies unit at KPMG (United Kingdom) and Harris Research (United Kingdom). The following three market segments were identified for personal handheld and fixed in-vehicle land mobile voice communication services: 1) international business travelers (IBTs) for users traveling internationally for business purposes to areas with incompatible cellular standards or no cellular services at all, 2) national roamers (NRs) for users who roam into areas not covered by cellular services within a particular country, and 3) cellular extensions (CEs) for business users who are based in regions not covered by any cellular networks.

The main study consisted of 1125 face-to-face interviews conducted in 10 countries chosen to represent the market both geographically and economically. A second in-depth simulation study using 200 people was also conducted to probe further into user cooperation issues and reinforce the main study. To develop a global addressable population, the interview sample data was extrapolated to regions that were not interviewed by relating known characteristics similar to the sample, such as IBT travel patterns. The study did not examine or include forecasts for commercial trucking, semifixed telephone booths, maritime or aeronautical segments, which will provide additional customers and markets.

Table 2 Breakdown of addressable population for year 2005

Market segment	Addressable population, millions of users	Annual minutes per user, minutes/year
IBT	3.8	650
NR	9.5	300
CE	2.4	1500
Total	15.7	8.92×10^9

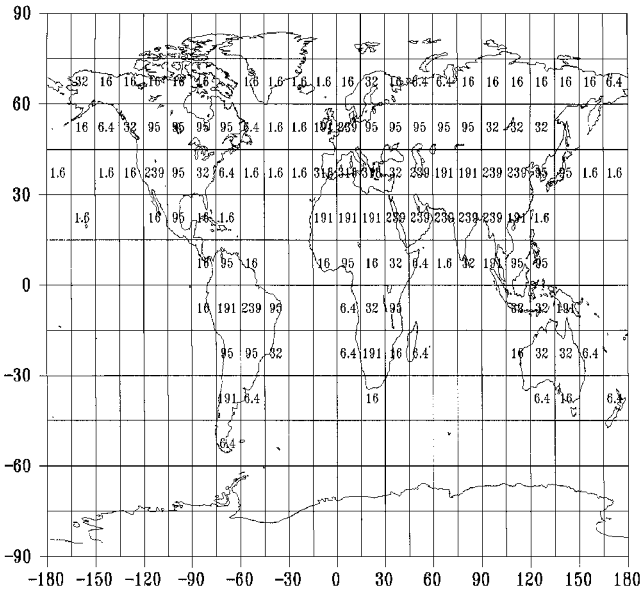

Fig. 1 Full market distribution of traffic in millions of minutes per year for 2005.

Utilization was based on interview information on the number of business trips, nights per trip, and calls per day, as shown in Table 2. No assumptions were made for other value added services such as facsimile, data, or messaging. Price sensitivity and the impact of transmission delay on the length of call were also taken into account. Some of the key product and service assumptions include a handset price of U.S. \$1500, end-user charge of U.S. \$2/min for satellite-delivered voice, handset size of 300 cm^3 and mass of 300 g, and 1 h of talk time with 24 h of standby time. The geographical market distribution for the full market is shown in Fig. 1 for the year 2005. The map is divided into 15° latitude and longitude traffic grids. Each grid contains the total number of addressable minutes in millions expected in the year 2005. User traffic is considered negligible in blank grids and is assumed to be zero.

The addressable market in 2005 was extrapolated from 2001 to 2012 by assuming a 4.5-year takeup half-life,[7] i.e., the market reaches half of its expected growth in the first 4.5 years and peaks

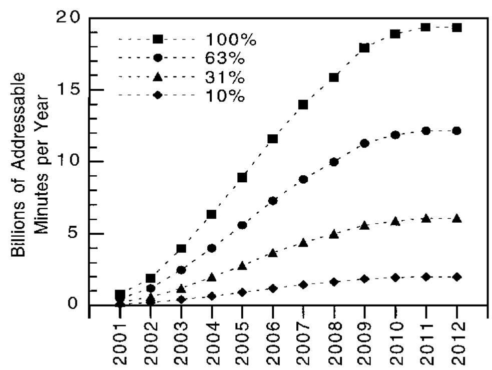

Fig. 2 Addressable market growth.

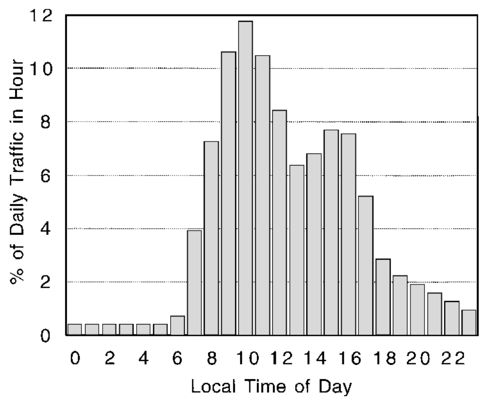

Fig. 3 Daily voice traffic pattern.

4.5 years later, as shown in Fig. 2. Included with the total market curve are the three market penetration levels examined. The market penetration level for any system will depend in part on how many systems become operational. The market studies showed that an MEO system, competing with one other major system, might be expected to achieve an overall 30% market penetration level. Although market penetration levels would be expected to vary from region to region, depending on many factors, the market penetration was assumed to be constant in all grids when evaluating the model systems.

Because of regional differences, as well as the penetration of terrestrial communications, user activity was not expected to grow at equal rates in each of the grids. Very high traffic regions are more likely to attract terrestrial cellular networks and alternative services, which will bound the growth of mobile satellite services in these areas. Likewise, it may not be cost effective for terrestrial cellular to service low traffic areas, and those areas can be expected to grow more rapidly as global communication becomes more important. To simulate the limiting effect of competition in high traffic areas, each grid was limited to a maximum grid traffic of approximately 400×10^6 voice-minutes per year. As the growth rate was applied to the traffic model in each successive year, all of the nonlimited grids were increased until the total traffic matched the total market growth displayed in Fig. 2.

Voice traffic varies dramatically during the day with peak hours around 10 a.m. and 3–5 p.m. local time. The daily voice traffic pattern displayed in Fig. 3 is from a typical day at a federal office building in Washington D.C.[8,9] Although these data represent primarily fixed voice traffic, the distribution displayed in the figure is also considered applicable for global, mobile voice services. Seasonal and weekly variations in voice traffic are considered negligible when compared to the time of day variations and yearly growth.

System Capacity

One of the key aspects in the design process of a communication satellite system involves the evaluation of the effective system capacity, which will be a function of many variables including traffic demand, coverage patterns, and other aspects of the satellite design. Because of the complex interaction between subscribers, orbiting satellites, gateways, and design constraints for nongeostationary systems, a computer simulation was developed to evaluate the useful capacity of model mobile satellite systems.[5,6] As the satellites are propagated during a simulation, the addressable traffic from the market model is determined for each satellite spotbeam in the modeled constellation. The major limiting capacity constraints are determined, including market penetration, spotbeam pattern coverage, mobile and gateway bandwidth limits, frequency reuse between satellites, available satellite power, spotbeam hardware power limits, power flux density (PFD) limits, multiple access techniques, CDMA self-interference limits, and fading and multipath link availability.

If the model system does not use satellite crosslinks to route voice traffic, the simulation also checks if there is an available gateway antenna in view and calculates the minimum number of PSTN connections required at each gateway site to connect the satisfied traffic. Outputs from the simulation include the useful system capacity in billable minutes, the number of PSTN connections required for each gateway site, the system availability, and a breakdown of the beam capacity limits.

The basic flow of the capacity simulation is shown in Fig. 4. The simulation inputs for each modeled system are contained in a control file, which contains the orbital elements for each satellite in the constellation, gateway locations, and details of the communications design, including frequency plan, multiple access scheme, maximum downlink rf power and spotbeam patterns, and power limits. The simulation begins by reading the control file for the model system, initializing the traffic model for the year of the simulation, and building some lookup tables, which will be discussed later.

The function of the simulation can be broken down into two iteration loops: the time cycle and the allocation cycle. The main loop,

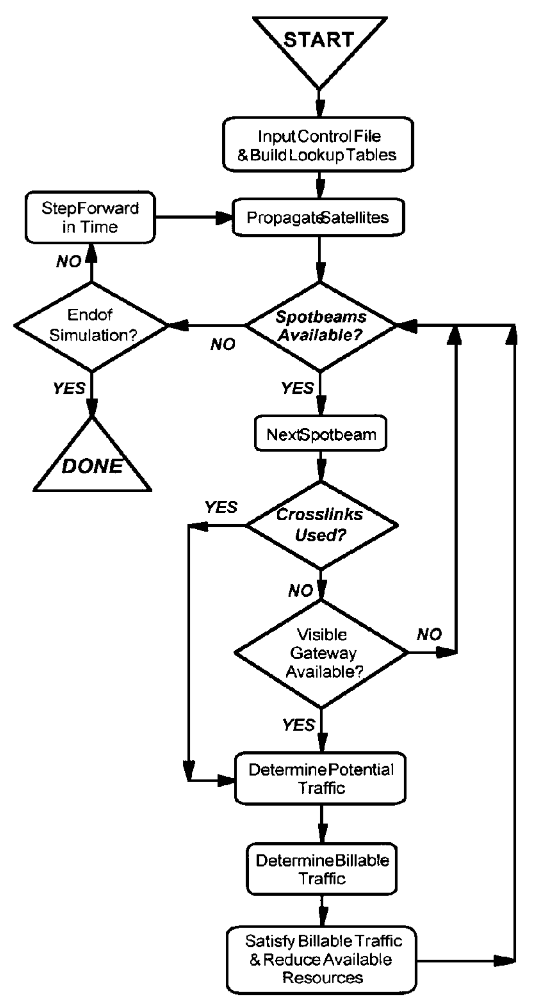

Fig. 4 Capacity simulation program flow.

the time cycle, advances the simulation clock, determines how many users are waiting for service throughout the world at that time, and updates the position of each satellite in the constellation. The inner loop, the allocation cycle, determines how many of these waiting users can be supported, within system constraints, and allocates the resources necessary to satisfy them. The steps involved in each of these loops will be detailed further.

Determine Potential Traffic/Propagate Satellites

At each step of the simulation clock, the number of potential voice circuits in each of the traffic grids throughout the world must be determined. The number of potential circuits (waiting users) available in each traffic grid is calculated by multiplying the average daily market in each grid for the simulation year (2001–2012) by both the fraction of voice traffic expected for the traffic grid's time of day (obtained from Fig. 3) and the percentage of market penetration assumed for the model system (10, 30, or 60%). Once the waiting traffic demand has been calculated, the simulation propagates the constellation forward in time and determines the new position of each satellite in the constellation. At this point, the simulation enters the allocation cycle.

Allocation Cycle

During the allocation cycle, the simulation steps through each spotbeam in the constellation, determining how much potential traffic is within the beam's field of view and satisfying as much of that traffic as possible within the system constraints. The order in which the spotbeams are checked is determined by the beam-limit table, which is built at the beginning of the simulation. The table contains the average forward downlink power required, per circuit, for each beam in the constellation sorted from lowest to highest. Cycling through the spotbeams in this order results in the largest possible system capacity for a given time step. As the simulation begins the allocation cycle for a given spotbeam, it first determines if the mobile traffic can be routed to a gateway antenna.

Gateway Visibility Check

A satellite can only serve traffic demand if it can route that traffic to a gateway antenna, either directly through line-of-sight communications or indirectly through intersatellite crosslinks. Although intersatellite links allow mobile-to-mobile calls, without the technical requirement to route each call directly to a gateway, calls between mobile and fixed users will still require connection to the PSTN through a gateway.

For the systems that do not use intersatellite crosslinks, the location and number of gateways needed for reasonable global coverage was estimated and used for each system's capacity simulations and cost estimates. Gateways were placed in various locations based on their observed coverage areas, and line-of-sight statistics were calculated to determine if there were any coverage gaps. The number and location of gateway sites, as well as the number of antennas per gateway, were varied until an apparent minimum occurred. Placement of the gateways in the model was limited to areas near cities so they could be easily connected into the PSTN. The actual number and location of gateway terminals will depend on political and marketing strategies, factors beyond the scope of this study. Table 3 lists the number of gateways and antennas used in the simulations. Although the gateway visibility check was disabled for systems utilizing crosslinks, the LEO66 costs included 30 gateway stations (Iridium expects approximately 30 gateway terminals for a mature system[10,11]) to ensure adequate access to the PSTN.

Table 3 Estimated number of gateway sites and antennas

	Number of gateways	Number of antennas per gateway[a]
LEO66	20	4
LEO48	28	5
HEO17	8	5
MEO12-48	6	5
MEO12-61	6	5
GEO3	3	2

[a]Includes one spare antenna per gateway site.

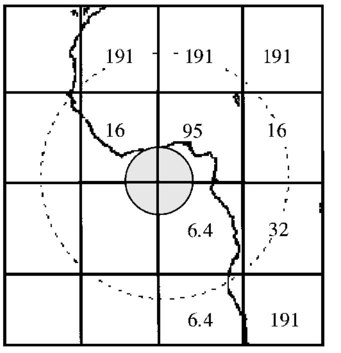

Fig. 5 Example of a beam covering multiple traffic grids.

The gateway visibility check (bypassed for systems that use crosslinks) ensures voice traffic can connect with the PSTN. At the beginning of every time step, each satellite in the constellation is assigned to the gateway antenna with the best line-of-sight geometry, provided one is available. A gateway antenna is considered available if the satellite is visible above a 10-deg elevation angle and the antenna has not already been assigned to another satellite. During the allocation cycle, the simulation verifies that the satellite has been assigned to an available gateway antenna. If the spotbeam passes the gateway visibility check, the simulation will then determine how many waiting users are located within the beam's field of view.

Determining Addressable Traffic

The potential traffic available to an individual spotbeam will vary as the satellite passes over changing market densities and time zones. As discussed earlier, the potential traffic waiting in each grid is determined at the beginning of each time step, and every satellite spotbeam is mapped onto the surface of the Earth. The shaded circle shown in Fig. 5 represents a single satellite spotbeam covering fractions of four grids with different traffic densities. If only a fraction of an individual traffic grid falls within the spotbeam's coverage area, then only a fraction of the potential traffic can be considered addressable to the spotbeam. Because the instantaneous traffic demand is assumed to be evenly distributed within each traffic grid, the number of users addressable by the spotbeam within an individual grid is equal to the potential traffic waiting within the grid multiplied by the fraction of the grid area falling within the spotbeam's coverage area. The total traffic available to the spotbeam is then equal to the sum of the grid traffic available from each of the grids within the spotbeam's coverage area.

Determining the grid area each beam covers during every step of the simulation would take a great deal of time. A beam-area table is created for each system at the beginning of the simulation to speed up the calculations containing the percentage of grid areas covered by each spotbeam on a satellite for a given subsatellite point. The table is built by placing the satellite above every possible degree of latitude and longitude (for circular orbits), mapping the spotbeams onto the traffic grids, and calculating for each spotbeam the percentage of each grid within the beam's field of view. Beam-area tables are created in a similar manner for satellites in elliptical orbits (provided the orbit has a frozen argument of perigee) by stepping the satellite position through each degree of mean anomaly and longitude. Using beam-area lookup tables in the simulation assumes that each satellite in the constellation (of a given orbital type) maintains the same yaw orientation throughout the simulation run and also ignores perturbation effects that can modify the shape of the orbit.

Determining Billable Traffic

Once the potential market for a beam is found, the next step is to determine the maximum number of users that the spotbeam is actually able to satisfy. The beam capacity will be limited by a number of constraints, including bandwidth limits, frequency reuse, available satellite power, maximum rf power per beam, PFD limits, multiple beam interference limits, and link availability.

The fundamental link equation for satellite-based digital communications, the basis for most of the capacity limit calculations in the simulation, represents the information-carrying capacity of the digital link.

Link Equation

The end-to-end basic link equation for a digital bent pipe system is

$$\frac{1}{(E_b/N_0)_{\mathrm{req}}} = \frac{1}{(E_b/N_0)_{\mathrm{mobile}}} + \frac{1}{(E_b/N_0)_{\mathrm{gateway}}} \tag{1}$$

where $(E_b/N_0)_{\mathrm{req}}$ is the energy per bit to noise density ratio required to achieve a given BER, $(E_b/N_0)_{\mathrm{mobile}}$ is the energy per bit to noise density ratio of the mobile link, and $(E_b/N_0)_{\mathrm{gateway}}$ is the energy per bit to noise density ratio of the gateway link. If the E_b/N_0 from the gateway is sufficiently large, its contribution can be assumed to be negligible and $(E_b/N_0)_{\mathrm{req}}$ can be expressed as

$$\left(\frac{E_b}{N_0}\right)_{\mathrm{req}} = \frac{P_t G_t G_r L_s L_c L_p L_B}{V_a RkTM} \tag{2}$$

If voice activity is used, the voice activity factor V_a is approximately 0.4 (Ref. 9). In a normal conversation, a person talks on average 40% of the time. Systems can take advantage of this by not transmitting when the person is silent. Notice that Eq. (2) uses the peak transmit power P_{peak} because

$$P_t = \frac{V_a RkTM(E_b/N_0)_{\mathrm{req}}}{G_t G_r L_s L_c L_p L_B} \tag{3}$$

If an onboard processing regenerative transponder is used, then the gateway link is separated from the mobile link and Eq. (2) is found directly. Equation (2) can be used for either uplink or downlink calculations by substituting the values associated with the appropriate link.

The beam-limit table determines the order in which the beams are checked. The average forward downlink power per circuit required for each beam is calculated for all of the satellites and sorted from lowest to highest. The capacity is allocated starting with the lowest power per circuit beam. This order results in the largest possible system capacity for a given time step. Solving Eq. (2) for P_{avg} and using average fading values gives the average downlink power per circuit needed to make the link,

$$P_t = \frac{V_a RkTM(E_b/N_0)_{\mathrm{req}}}{G_t G_r L_s L_c L_p L_B} \tag{4}$$

One of the first constraints imposed on the beam involves link availability, which depends on the environment of the subscriber and the maximum fading and blockage margin available. Because the handheld power is limited by safety constraints, the blockage margin on the return uplink will determine the link availability. Combining Eq. (2) with Eq. (3), and solving for the fading and blockage losses gives

$$L_B = \frac{V_a RkTM(E_b/N_0)_{\mathrm{req}}}{P_t G_t G_r L_s L_c L_p} \tag{5}$$

The maximum handheld transmit power, $P_{\mathrm{peak}}(P_{\mathrm{avg}}/V_a)$, is used to determine the maximum blockage margin. The beam center elevation angle and maximum blockage margin are then used with shadowing and fade statistics[6] to find the availability for an assumed average customer distribution of 10% urban, 50% suburban/tree-shadowed, and 40% rural environments. The addressable beam traffic is divided into those three environments and decreased by the availability percentages determined for each environment.

Bandwidth Limits

When the satellites are propagated, their footprints overlap by various amounts, reducing their ability to reuse bandwidth. The more the satellite footprints overlap, the fewer bandwidth channels each satellite can use. The overlap table determines how many mobile bandwidth channels are available at every beam location.

The overlap table is built at the beginning of the capacity simulation by propagating the full constellation and recording the number of satellites in view above the minimum coverage elevation angle at every latitude and longitude. When averaged over a long period of time, the overlap between satellites in circular orbit (at the same altitude) varies mostly with latitude for the systems and is fairly constant with longitude. The number of satellites in view is averaged over longitude and time to find the average overlap for each latitude. To estimate the bandwidth channels available on the mobile link for a spotbeam, the nominal number of bandwidth channels is divided by the overlap factor for the beam center. For the GEO3 system, the overlap table was set equal to one for all latitudes because the beam patterns are customized and the satellites are stationary with respect to Earth. The overlap table for the HEO17 system, due to its elliptical orbiting satellites, was built in a different manner. HEO17's elliptical orbits, because they are sun synchronous, maintain the same orientation with respect to the sun. Hence, the orbital coverage for the HEO17 system is a function of the position of the sun and, therefore, of local time. Thus, HEO17's overlap table was extended to store the average number of satellites in view above a minimum elevation angle at each latitude and each hour of local time.

The amount of bandwidth a system can use is regulated by the International Telecommunications Union (ITU) and regional regulatory bodies. The Federal Communications Commission's (FCC's) basic sharing plan for the mobile link allocates 5.15 MHz of bandwidth in the L-band for a time division duplex/TDMA system. The CDMA systems have been allocated 11.35 MHz for the return uplink in the L-band and 15.5 MHz in the S-band for the forward downlink. Each of the systems plans to channel the mobile bandwidth differently. A 14-MHz bandwidth with one channel is used for GEO3 because it was based on the Tritium design proposed by Hughes.

CDMA and TDMA systems are bandwidth limited in different ways. A TDMA system has one time slot for each subscriber on a frequency channel. Frequency channels can be reused, but only if they are separated spatially. The bandwidth limit is a hard boundary for TDMA systems that is equal to the number of frequency channels and time slots available. CDMA does not have a hard bandwidth limit on capacity but is interference limited on the return uplink because many users concurrently share bandwidth channels. As each additional circuit is added in a bandwidth channel, the quality of all of the circuits is slightly degraded. Bandwidth channels can be reused in every beam, but if beams with the same bandwidth channels overlap, the total interference-limited capacity for the overlapping beams does not change and must be divided between them.

Synchronous direct sequence CDMA (DS-CDMA) with orthogonal codes will most likely be used for the forward downlink from the satellite to the mobile users. Because the orthogonal codes are synchronized, there is little cross correlation between individual signals resulting in minimal self-interference. On the return link, however, synchronizing all of the individual handheld units proves to be a difficult problem and asynchronous DS-CDMA will most likely be used. Because the signals are not synchronized, the uplink can be self-interference limited. In a given beam, each user's signal in a bandwidth channel acts as noise to every other user in the channel. The self-interference noise density can be expressed as

$$I_{\mathrm{self}} = \frac{N_I C V_a g_p}{B} \tag{6}$$

where C is the uplink signal and B is the spread bandwidth of the uplink CDMA channel. The number of interfering users N_I is then given by

$$N_I = (N_u - 1) + m \cong \alpha N_u \tag{7}$$

where N_u is the number of users transmitting within the frequency band and m is the equivalent number of users contributing interference power from other beams and frequency bands. For satellite-based mobile systems, α was assumed to be 1.25. C is given by

$$C = \frac{P_t G_t G_r L_s L_c L_p L_0}{V_a} \tag{8}$$

where average values for handset power and fading are used. Assuming the gateway link contribution is negligible, the return link is given by

$$\left(\frac{E_b}{N_0}\right)_{\text{req}} = \frac{C}{R(kT + I_{\text{self}})} \tag{9}$$

Solving the preceding equations for N_u gives the interference-limited number of circuits possible in a CDMA bandwidth channel on the return uplink

$$N_u = \frac{B}{\alpha V_a g_p R}\left(\frac{1}{(E_b/N_0)_{\text{req}}} - \frac{V_a RkT}{P_t G_t G_r L_s L_c L_p L_0}\right) \tag{10}$$

PFD Limits

The ITU and FCC regulate the maximum rf power received at the surface of the Earth based on the PFD (watt per square meter) in a 4-kHz bandwidth. The following limits are imposed by the ITU radio regulations for the S-band mobile downlink[12]: -152 dB (W/m^2/4 kHz) for 0 deg $\le \varepsilon < 5$ deg, $-152 + 0.5(\varepsilon - 5)$ dB (W/m^2/4 kHz) for 5 deg $\le \varepsilon < 25$ deg, and -142 dB (W/m^2/4 kHz) for $\varepsilon \ge$ 25 deg, where ε is the elevation angle of the link in degrees above the horizontal plane. Because the mobile downlink in the L-band is classified as secondary, it does not have a specific PFD limit. Instead, a secondary system must not cause any harmful interference to or claim protection from any primary service in the band.

The PFD per 4-kHz bandwidth on the surface of the Earth is given by

$$\text{PFD} = \frac{P_{\text{ch}} G_t L_c}{4\pi S^2}\left(\frac{4000}{B}\right) \tag{11}$$

where P_{ch} is the total power in watts transmitted in a bandwidth channel B Hz wide. Solving for the total power allowed per bandwidth channel gives

$$P_{\text{ch}} = \frac{4\pi S^2 \text{PFD}}{G_t L_c}\left(\frac{B}{4000}\right) \tag{12}$$

The PFD-limited capacity in a bandwidth channel is found by dividing the total power allowed per bandwidth channel from Eq. (12) by the average power required per circuit from Eq. (4). Because TDMA has multiple time slots, the instantaneous number of circuits is multiplied by the number of downlink time slots in a frame.

Satellite Power Limits

The power to a beam could be constrained by the available power from a beam, a group of beams, or the satellite. To find the power-limited capacity of a beam, the available rf power is divided by the average power per circuit from Eq. (4) and multiplied by the number of downlink time slots in a frame. The rf power is decreased from the beam groups and satellite power as it is used for each beam. The following assumptions are used to estimate each satellite's maximum downlink rf power[13]: 1) communications payload dc power to satellite dry mass ratio of 2 W/kg, 2) for digital signal processing payloads, 12 W per beam is assumed for digital processor and receiver power, 3) for simple bent-pipe repeater payload, 1 W per beam is assumed for receiver power, and 4) dc to rf power conversion efficiency of 20%.

The maximum downlink rf power assumed for model systems with onboard digital processing (LEO66) can be determined by the following equation:

$$P_{\text{rf}} = [(2\,\text{W/kg})M_{\text{dry}} - (12\,\text{W/beam})N_B]\varepsilon_{\text{dc to rf}} \tag{13}$$

Table 4 Average forward downlink satellite rf power

System	RF power, W
LEO66	128
LEO48	136
HEO17	257
MEO12-48	475
MEO12-61	871
GEO3	1093

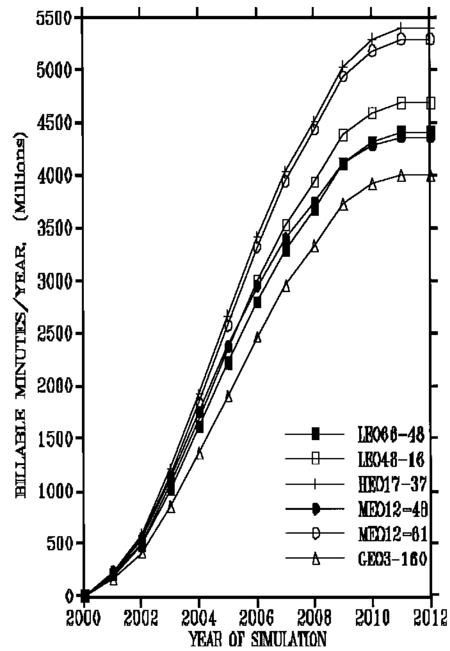

Fig. 6 Useful capacity results with 30% market penetration.

If the system operates as a simple bent-pipe repeater, then the maximum downlink rf power assumed can be determined by

$$P_{\text{rf}} = [(2\,\text{W/kg})M_{\text{dry}} - (1\,\text{W/beam})N_B]\varepsilon_{\text{dc to rf}} \tag{14}$$

Table 4 lists the available satellite rf powers assumed for the model systems.

Satisfy Billable Traffic

After all of the potential capacity limits for a beam have been determined, the most limiting constraint is chosen, compared to the beam's addressable traffic, and the smaller of the two is considered the number of billable minutes for the beam. This assumes both the number of circuits and the market demand are constant throughout the time step. The number of billable minutes is then subtracted from the market grids in the same proportions that it was originally available (based on area covered), because the same users cannot be served by more than one spotbeam. The number of billable minutes for the beam is then multiplied by the number of minutes used for the orbit propagator time step (3 min) and added to the total billable minutes achieved by the system. The process repeats for the next highest power per circuit beam until all of the beams have been utilized. The waiting market, available powers, and bandwidth channels are then reset, and the satellites are propagated to the next time step. The simulations were run for each of the model systems at 3-min time steps for one day per year (2001–2012). The total billable capacity determined for each run was multiplied by 365 days per year to determine the number of billable minutes satisfied during the year.

Estimated System Capacity Results

An example of the type of results that can be found from the capacity simulations are given in Fig. 6 for 30% market penetration (similar results were obtained for 10 and 60% market penetration levels). The capacity results indicate that there is sufficient room in the market for multiple systems, inasmuch as none of the model systems could satisfy the entire market. At lower market levels, the HEO17 system was able to satisfy the largest portion of the market due to its higher average elevation angles and link availability. As market size increased, the LEO systems satisfied larger capacities than the other systems. The GEO system was mainly limited by poor link availability due to its low-elevation angle coverage in high-latitude regions.

System Cost

The second half of the cost per billable minute metric consists of the life cycle costs required to develop, deploy, and operate each model system over its full system life. The total life cycle costs (TC_{sys}), shown in Fig. 7, include both the nonrecurring (NRE) costs associated with developing and testing the satellite and gateway designs and the recurring (RE) costs incurred during the production and operations phases of the system life. During the production phase, costs are incurred by building the operational satellites and gateways and launching the satellites into their operational orbits. Launch insurance costs are also included as commercial companies will likely want to mitigate their launch risks. Costs incurred during the operations phase include installation of PSTN interface hardware and personnel costs associated with gateway operations. Development costs for control centers, billing systems, handsets, advertising, etc., were not included as they are considered to be similar across systems and assumed equal for comparison purposes.

Each of the cost centers was estimated using parametric, or top-down, cost estimation techniques. This type of analysis utilizes mathematical relationships between costs and individual drivers (such as mass, power, weight, number of transponders, etc.) that are shown statistically to have a predictable effect on the cost. These relationships, derived from regression analysis of available historical data, assume that the cost of future units will remain dependent on the same drivers that affected the costs of similar units in the past. Parametric analysis can consist of multiple methods ranging from "high level, one CER (cost estimating relationship) approaches, such as dollars-per-pound *rules of thumb*, to lower level, multiple CER approaches."[14] High-level, industry rules of thumb can be especially useful when comparing different design approaches and only top-level design characteristics are available. This study utilizes a range of parametric approaches to estimate the various costs of the model systems.

The FCC has required the systems to become fully operational within 6 years of receiving a license. Because Iridium, Globalstar, and Odyssey received licenses in January 1995, they must become fully operational by the beginning of 2001. In reality, the systems began development at different times and may not become operational in the same year. For comparison purposes, all of the model systems are assumed to become fully operational at the beginning of 2001 after a 6-year development period for the first generation. Revenue is assumed to begin when the system becomes fully operational and continue for 12 years. Recurring costs are estimated over a 12-year operational lifetime to account for differences in satellite lifetimes. The LEO satellites are assumed to have a useful lifetime of five to seven years and require two full generations. The number and design of the second-generation satellites are assumed to be identical to the first generation including ground and on-orbit spares. Second-generation costs are spread over four years with the last launch occurring six years after the final launch of the first generation. MEO and GEO systems are assumed to require one generation of satellites.

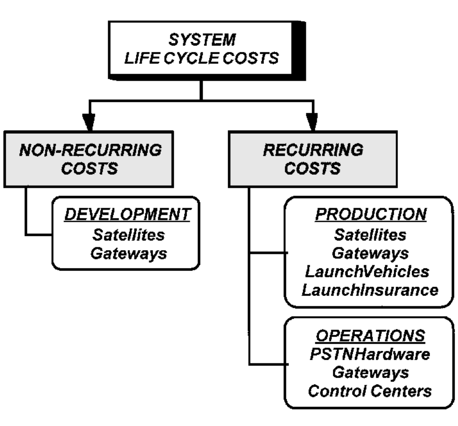

Fig. 7 Life cycle cost breakdown.

Space Segment

A number of detailed cost models were considered for the study, including the U.S. Air Force's unmanned space vehicle cost model (USCM7) (Ref. 14) and The Aerospace Corporation's small satellite cost model (SSCM).[15] Neither of these multilevel CER models could be utilized due to lack of design detail and because many of the model systems' design parameters were well outside the recommended ranges (especially for SSCM). Because of these factors, satellite life cycle costs were estimated using an industry rule of thumb relating the dry mass of a satellite with its theoretical first unit (T_1) cost. Industry experience has shown a trend of \$77,000 fiscal year 1994 (FY94) per kilogram of dry mass for current mobile communication satellite systems.[13]

$$T_1 = \$77{,}000 \times \text{dry mass} \tag{15}$$

A common technique for estimating unit recurring costs is to extrapolate them from their theoretical first unit cost (T_1). Although the T_1 cost represents the theoretical cost of the first unit, it is necessary to consider learning curve theory to estimate the cost of many units. The learning curve is a mathematical technique used to account for the observed reduction in costs as larger numbers of units are produced. These cost reductions are experienced due to productivity improvements caused by many factors, including human learning as workers become more adept at performing repetitive tasks, economies of scale achieved by purchasing materials in bulk, and changes in design, tooling, and management applied during the production phase.[16] From cumulative average theory, the total recurring cost of producing N units is described by

$$\text{RE} = T_1 N^{\{[\ell n (S_L)/\ell n (2)] + 1\}} \tag{16}$$

The learning curve slope S_L represents the percentage reduction in the cumulative average cost when the number of production units is doubled. Determining a valid learning curve slope to use for some of the LEO systems is difficult, inasmuch as the large number of satellites involved requires a production rate previously unknown in the commercial satellite industry.[3] For this study the following learning curves were assumed: 95% curve for under 10 satellites, a 90% curve for 10–50 satellites, and an 85% curve for 50–100 satellites.[17] Table 5 lists the number of satellites (including spares) required for each generation, along with the dry masses used for the cost estimates.

NRE development costs are estimated at three to six times the first unit RE cost. Industry cost analysts generally assume an NRE factor of two for a new design based on current practices, a factor of three for a state-of-the-art design, and a factor of four to five when pushing the state of the art. Cost data from the USCM7 model for communication satellite programs (DSCS-IIIA, FLTSAT-1, GPS Block I, GPS Block II/IIA, Intelsat-IV, Marisat, NATO-3, TACSAT, TDRSS) show an average NRE factor of 3.44. The following NRE factors were used for the purposes of this study.

The LEO systems are complex and challenging due to the large numbers of satellites and the frequent call handoffs required at their

Table 5 Number of satellites and dry mass for model systems

Model	First generation		Second generation		Dry mass,
systems	Operational	Spare	Operational	Spare	kg
LEO66	66	14	66	14	607
LEO48	48	8	48	8	349
HEO17	17	3	17	3	662
MEO12-48	12	2	0	0	1212
MEO12-61	12	2	0	0	2207
GEO3	3	1	0	0	2812

Table 6 Estimated number of launch vehicles for first generation and costs/launch, FY94 $$10^6

	Cost per launch		Number of launches/satellites per launch					
Vehicle	Range	Modeled	LEO66	LEO48	HEO17	MEO12-48	MEO12-61	GEO3
Ariane-4	77–141 (Ref. 28)	100			3/3	4/2		
Ariane-5	118–130 (Ref. 28)	125			1/7		3/2	4/1
Delta-II	49–60 (Ref. 28)	50 (Ref. 26)	9/5	5/4	2/2	6/1		
Long March	24–55 (Ref. 28)	45 (Ref. 20)	7/2					
Proton	59–82 (Ref. 28)	70	3/7				3/2	
Soyuz	18 (Ref. 28)	18					2/1	
Zenit	35–65	40 (Ref. 27)		3/12				

low altitudes. The LEO48 system will require the production of 56 satellites in a few years, which would exceed any satellite production rate ever achieved in the commercial satellite world.[3] These production rates will require high-volume manufacturing techniques, which will require a larger initial investment. An NRE factor of five was assumed for the LEO48 system to represent these design challenges. The LEO66 system will also require high-volume manufacturing techniques, but a higher factor of six was modeled due to its much more complex design. Whereas the other model systems will operate as simple bent-pipe repeaters, the LEO66 system will utilize onboard digital signal processing techniques, active call switching, and intersatellite crosslinks to route signals through its network. The HEO17, MEO and GEO satellite systems are assumed to have an NRE cost of three times the first unit because they are similar to previous satellite designs and the smaller number of satellites will allow for more traditional satellite manufacturing methods.

Launch Vehicles and Insurance

Launch costs are expected to be a major factor in the total systems cost; especially for the LEO systems due to the large number of satellites involved. Table 6 lists the launch vehicle assumptions used, including the launch vehicles, number of launches, and number of satellites per launch. The launch assumptions were modeled in part after published launch plans of some of the proposed systems.[18–27] In addition to the operational satellites, each system was required to launch all ground and on-orbit spares to replace satellites that fail on-orbit during the system life. Second generation launch requirements for the LEO/HEO systems are assumed to be identical to the first generation. Table 6 also lists a range of observed launch costs, for each of the launchers, available from NASA.[28] The modeled launch costs were selected from this range, unless published launch costs were available in the literature.

Because approximately three-quarters of satellite losses occur during the launch phase,[29] it is expected commercial companies deploying a satellite constellation will purchase launch insurance. Launch insurance generally mitigates risk from ignition until the vehicle is pronounced operational in its intended orbit. Typical launch insurance rates have varied between 16 and 20% of the insured value.[30] Launch insurance costs are estimated at 20% of the combined satellite and launch costs to cover the cost of replacement satellites and launch vehicles in the event of a launch failure. Although second generation launch plans are assumed to be identical to the first, launch insurance costs will decrease due to the reduced recurring cost of the second generation satellites.

Ground Segment

Ground segment costs, which are largely dependent on the system design, include gateways to communicate with the satellites, hardware to connect to the PSTN network, and people to operate the system.[5,6] Gateway costs are estimated from the number of antenna and gateway sites needed for reasonable global coverage as described previously. A K_a-band tracking ground station is assumed to have an average recurring cost per antenna of $\$1.5 \times 10^6$ for LEO, $\$2.5 \times 10^6$ for MEO/HEO, and $\$5.0 \times 10^6$ for GEO systems.[13] These costs, which vary depending on the slew rate and noise figure requirements and the amount of redundancy required, include all of the hardware necessary to convert the signal down to baseband. The connection of the baseband signal to the PSTN is determined separately. An NRE factor of five times the cost of the first complete ground station is also assumed. Each individual gateway is expected to have a lifetime of over 12 years.

Operation costs are estimated by assuming four, five-person shifts to operate each gateway site. The cost to support one person is assumed to be $150,000 per year. Operation costs for the gateways are assumed to begin two years before final launch of the first generation and continue to the end of the system life.

The electronics necessary to interface the gateway baseband signals with the PSTN are available in individual blocks based on voice channel capacity. These connections are expected to have a recurring cost of $\$1.5 \times 10^6$ for every 400 duplex voice channel blocks.[13] Installation of an initial block of 400 voice channels is required for each gateway site prior to becoming operational, after which fractions can be added as needed. The minimum number of PSTN hardware connections required to connect the gateways with the PSTN network is calculated from the capacity simulations. While determining the number of billable minutes, the capacity simulation also kept track of the peak traffic experienced throughout the year at each gateway site. Yearly PSTN hardware requirements for the LEO66 system is estimated by keeping track of the peak global traffic experienced at any time because its intersatellite links can potentially route calls to gateways that have PSTN connections available. Operations and PSTN hardware connection costs are added in the years they are incurred. Operation costs for the gateways are assumed to begin 2 years before the final launch of the first generation and continue to the end of the 12-year system life.

Estimated System Cost

A summary of the system costs for each cost element, except for operational and PSTN hardware costs, is provided in Table 7. Although the system costs are listed in a lump sum, they will actually be expended over a range of years. An analytical method to spread costs, based on the experience of actual programs, was developed by Wynholds and Skratt.[31] The following function represents the approximate spreading of program costs over the system lifetime:

$$F(T_f) = [10 + T_f(6T_f - 15)]T_f^3 \tag{17}$$

where T_f is defined as the fraction of total time elapsed and $F(T_f)$ is the fraction of cost consumed in time T_f. This equation assumes 50% expenditure at the midpoint of design and production. The development, production, and deployment costs of the two satellite generations were spread separately and combined with the continuing operations and PSTN costs. The total spread system life cycle costs for 30% market penetration are shown in Fig. 8. The spread costs for the LEO systems have two large peaks, which correspond to the construction and launch of the first and second generation satellites. The life cycle costs are the highest for the model LEO systems.

Cost per Billable Minute

The net present value is the net value of a time-dependent cash flow discounted to its equivalent present value. In the mobile satellite case, the cash flow is the end-of-year costs associated with building and maintaining the system and the subsequent revenue stream from the billable minutes. The net present value (NPV) is found by

$$\mathrm{NPV} = \sum_{i=1}^{n} \left[\frac{x_i}{(1+d)^i} \right] \tag{18}$$

Table 7 Cost center summary, FY94 $\$10^6$

Model system	LEO66	LEO48	HEO17	MEO12/48	MEO12/61	GEO3
			NRE costs			
Satellites	280.6	134.4	152.9	280.0	509.8	649.6
Gateways	30.0	37.5	62.5	62.5	62.5	50.0
Total	310.6	171.9	215.4	342.5	572.3	699.6
			First-generation RE costs			
Satellites	1338.9	585.6	646.5	874.8	1592.8	781.7
Gateways	180.0	210.0	100.0	75.0	75.0	30.0
Launch	975.0	370.0	525.5	700.0	621.0	500.0
Launch insurance	462.8	191.1	234.3	315.0	442.8	256.3
Total	2956.7	1356.7	1505.8	1964.8	2731.6	1568.00
			Second-generation RE costs			
Satellites	937.2	409.9	517.2	n/a	n/a	n/a
Launch	975.0	370.0	525.0	n/a	n/a	n/a
Launch insurance	422.6	173.6	221.4	n/a	n/a	n/a
Total	2334.8	953.5	1263.6	n/a	n/a	n/a

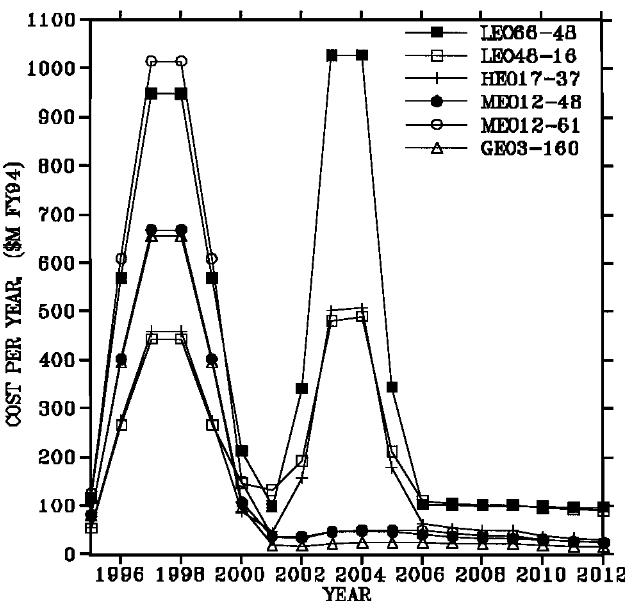

Fig. 8 Estimated spread system costs for 30% of expected market.

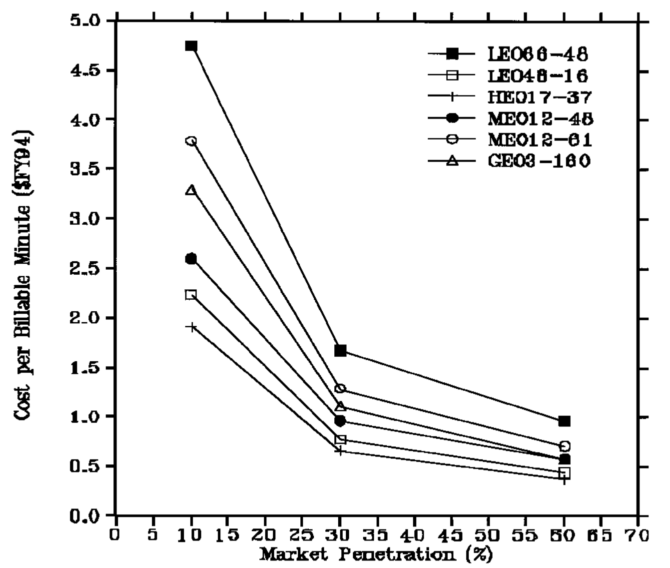

Fig. 9 Cost per billable minute for the model systems.

where x_i represents the constant-year dollar, before tax cash flow for each year, determined by subtracting the yearly cost from the yearly revenue. The internal rate of return is simply the discount rate at which the net present value of the cost and revenue cash flow is equal to zero. As already described, the system costs for each generation were spread over the appropriate development period, whereas the operations and PSTN costs were added the year they were incurred. The yearly revenue is equal to the cost per billable minute multiplied by the number of billable minutes (determined by the capacity simulation) satisfied during the year. For each of the systems, the cost per billable minute is determined from Eq. (18) such that the net present value is zero for a 30% discount rate. Although the 12-year operational lifetime was chosen to compare the systems on a normalized timeline, it is recognized that investors may require a return sooner than 12 years.

The cost per minute metric results for model systems with 10, 30, and 60% penetration of the market are shown in Fig. 9. These results are largely dependent on the assumptions made in this study. However, a number of important conclusions can be drawn from the metric. The first is that all of the model systems are technically capable of meeting the requirements. Furthermore, all of the model systems are economically viable with sufficient market penetration. For all of the modeled systems, the metric decreases as a function of market penetration. This is a result of having more customers over which to amortize the system costs. It also indicates that none of the systems have saturated at 60% market share. Given equal market penetration, the HEO17 and LEO48 were the lower cost per billable minute systems and the LEO66 system was the highest. However, note that for unequal market penetration the LEO66 system will be less expensive than most of the others if it has as much as 60% of the market. This indicates the importance of being first to market for relatively similar technical capabilities. Finally, there is no clear trend in the metric with regard to choice of orbital altitude or number of satellites. This indicates that the choice of system architecture to achieve the requirements is relatively insensitive to these parameters as long as other factors do not come into play. One of these factors might be latency time. Another factor might be the probability that a call might be dropped. These factors will affect customer choices and, thus, will impact the system architecture choice.

Conclusions

The cost per billable minute metric measures how cost effectively a system design satisfies an expected market. The methodology described provides a systems level perspective that takes into account major factors affecting system viability: the potential market, usable system capacity based on the system design, level of market penetration, and system cost and time value of money.

Several example systems were modeled to demonstrate the utility of the metric and illustrate how different architectures and assumptions can affect the results. The use of a single metric to evaluate technical, cost, schedule, and market issues allows meaningful system level trades to be performed. Potential additional applications of the cost per billable minute methodology include examining broadband satellite systems, regional geostationary vs global satellite systems, and the little LEO short-message satellite systems.

The systems modeled in this paper are only roughly similar to some of the proposed systems and should not be used as an indicator of their success. To perform a cost per billable minute comparison of actual systems, the models and assumptions would need to be refined to reflect the unique differences associated with the individual companies. In addition, other company-dependent factors such as regulatory approval, access to markets, and financial resources would need to be considered.

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