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A comparison study of CDMA versus TDMA/FDMA LEO satellite systems

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A COMPARISON STUDY OF
CDMA VERSUS TDMA/FDMA
LEO SATELLITE SYSTEMS

by

Timothy Michael Ciocco

March, 1996

Thesis Co-Advisors: Paul H. Moose
R. Clark Robertson

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A COMPARISON STUDY OF CDMA VERSUS TDMA/FDMA LEO SATELLITE SYSTEMS

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In this thesis, two LEO satellite systems with different multiple access schemes are analyzed. The first system, GLOBALSTAR, uses CDMA. Equations are developed to calculate the maximum capacity of one satellite, of one satellite's user beam, and of the entire GLOBALSTAR system over CONUS. A detailed description of GLOBALSTAR's outage probability, the probability that a call will be dropped from the system or blocked from connection with the system, is given and graphed against varying average call time and varying call arrival rate. The second system, IRIDIUM, uses TDMA/FDMA. Equations are similarly developed to calculate the maximum capacity of one satellite, of one satellite's user beam, and of the entire IRIDIUM system over CONUS. The probability of success or failure of an IRIDIUM subscriber obtaining a system channel is given by the Erlang Loss Formula and graphed against varying average call time and varying call arrival rate. Results show GLOBALSTAR provides five times the service capacity of IRIDIUM over CONUS and provides a better probability of obtaining a system channel for a call than will IRIDIUM.

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I. INTRODUCTION

A. DISCUSSION

The majority of current satellite telecommunications involves the use geostationary satellites. Geostationary satellites appear stationary at one spot in the sky at an altitude of 35,786.0 kilometers (22,236.4 statute miles) [Ref. 1: p.1]. While there are certain advantages to be enjoyed and exploited in the use of geostationary satellites, such as no requirement for a tracking antenna, there also are definite disadvantages. With such a high altitude, geostationary satellites have large propagation delays, long inter-satellite link delays, high on-board power requirements, and high earth station power requirements.

Current technology and market demand have forged a new satellite technology that can alleviate some of the problems encountered with the geostationary satellites. This new technology is low earth orbiting (LEO) satellite technology. LEO systems orbit at an altitude between 650.0 - 1450.0 kilometers (403.9 - 901.0 statute miles) in non-geosynchronous orbits. This lower orbit permits reduced power for earth station transmissions to successfully communicate with the LEOs and provides the feasibility of creating a worldwide, wireless communications network.

LEO technology is relatively new to the telecommunications industry. There are currently less than ten competing LEO systems in development and/or implementation. All of these systems are designed very differently, with the type of multiple access scheme used being one of the largest differences.

These design differences result in a relative lack of an industry standard. While this provides for keen competition, it leaves the potential future consumer, such as the U.S. Department of Defense (DoD), no benchmark comparison. The DoD will undoubtedly desire to incorporate a LEO satellite system into its Defense Information Systems Network and must have a benchmark to compare different systems.

B. GLOBALSTAR LEO SATELLITE SYSTEM

Loral Cellular Systems, Incorporated, is developing the GLOBALSTAR LEO satellite system. Loral Cellular Systems was formed by Loral Aerospace Corporation, and Qualcomm, Incorporated. Their LEO system will work with the existing public switched telephone network (PSTN), cellular networks, private and specialized networks, and personal communications networks to provide global, mobile voice and data services to and from hand-held and vehicle-mounted transmit and receive devices [Ref. 2: p.1]. GLOBALSTAR will use only classic "bent-pipe" communications technology in its satellites.

GLOBALSTAR's most significant feature is its use of Code Division Multiple Access (CDMA). CDMA is a modulation and multiple access scheme based on direct sequence spread spectrum communications techniques [Ref. 3]. The method of CDMA implementation chosen by Qualcomm for GLOBALSTAR employs a combination of frequency division, pseudo-random code division, and orthogonal signal multiple access techniques.

In CDMA, the desired signals are spread by the use of a pseudorandom-noise binary sequence [Ref. 2: Appendix 5, p.14]. In contrast to other systems, each signal in CDMA actually occupies a larger bandwidth (BW) than normally required. It is this spreading, coupled with a low transmit power requirement, that has produced estimates of a 10 to 20 times capacity increase using CDMA over other multiple access techniques [Ref. 4: p.45].

C. IRIDIUM LEO SATELLITE SYSTEM

Motorola Satellite Communications (SATCOM), Incorporated, is developing the IRIDIUM LEO satellite system. Motorola SATCOM, together with Lockheed-Martin, Raytheon, Scientific-Atlanta, and a host of global launch providers, plan to together make IRIDIUM a functioning entity.

IRIDIUM is a LEO satellite system designed to provide a wireless personal communications network [Ref. 5]. It will provide a wide range of telephone services, including voice, data, fax, and paging, to connect users anywhere in the world. It, unlike GLOBALSTAR, provides on-board demodulation and signal processing and will provide a complex myriad of satellite-to-earth, earth-to-satellite, and satellite-to-satellite links using processing links.

For its multiple access method, Motorola has chosen to use a combination of Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). In TDMA, a frequency channel is divided into a number of non-overlapping time slots; an individual user occupies an individual time slot that is usually separated from adjacent slots by a guard band. In FDMA, the available link spectrum is divided into a number of frequency channels. Each signal is bandpass filter limited to occupy only one frequency channel, and every signal requires its own channel. Motorola asserts that its choice of TDMA/FDMA multiplexing for its multiple access scheme on IRIDIUM makes the most efficient use of the limited spectrum available for LEO satellite systems [Ref. 5].

D. OBJECTIVE

Two major leaders in the telecommunications industry, Motorola and Qualcomm, are proposing two entirely different multiple access techniques for two different LEO satellite systems. Both systems have hard capacity limits. Capacity will be discussed in detail in Chap. II and Chap. III. That is, assuming the satellite is operating at optimal power output and over a given geographical area with a heavily populated and evenly distributed population, the system's users will have a limited number of time, frequency, and/or orthogonal CDMA slots. With all conditions being ideal and no external interference, these limited number of slots provide a hard capacity limit.

Equally as important as the hard capacity limit is the blocking probability (P_B), sometimes referred to as the outage probability (P_{out}). These two probabilities are roughly equivalent and stand for the probability that a call cannot get into a system or is dropped from the system. This probability extends the concepts of hard capacity limits to include the mean time of a call, the call arrival rate, hand-off capabilities of a system, power requirements, and a host of enhancing factors.

LEO satellite systems will be a major contributor in handling the demand for personal, mobile telecommunications well into the next century. The DoD and private consumers must have a benchmark to be able to compare CDMA and TDMA/FDMA LEO satellite systems. A hard capacity and P_B (P_{out}) comparison will provide potential users with guidelines for future communications systems implementations.

E. DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

II. GLOBALSTAR

A. SYSTEM DESCRIPTION

1. Space Segment

The GLOBALSTAR LEO satellite system will use a constellation of 48 non-geostationary satellites [Ref. 6: p.2]. These 48 operational satellites will be in eight inclined circular orbital planes of altitude 1,414.0 kilometers (878.6 statute miles). The inclination of the orbital planes is 52 degrees, the separation between the planes is 45 degrees, and the service arc is 360 degrees [Ref. 6: p.38].

The satellites employ classic bent-pipe repeater technology. That is, there is no onboard processing [Ref. 2: p.20]. The satellites receive a signal from either the gateway (earth) station or the mobile user, frequency translate it, and then retransmit the signal. There are no satellite-to-satellite links, only gateway-to-satellite links (and vice versa) and mobile-to-satellite links (and vice versa). This design was chosen to minimize the cost of GLOBALSTAR's space segment and utilize the already established terrestrial telecommunications networks.

To facilitate this bent-pipe technology, each satellite is equipped with two sets of 16 transponders. The first set of transponders are provided for the forward C-Band to S-Band path [Ref. 6: p.21]. The second set of transponders are provided for the reverse L-Band to C-Band path. The L-Band and S-Band antennas are configured to produce 16 beams covering an area of 61.5 million square kilometers (24.8 million square statute miles) as illustrated in Fig. 2.1 [Ref. 6: p.20]. They will operate with left hand circularly polarized polarization. The C-Band feeder links will operate with both LHCP and right hand circularly polarized (RHCP) polarizations.

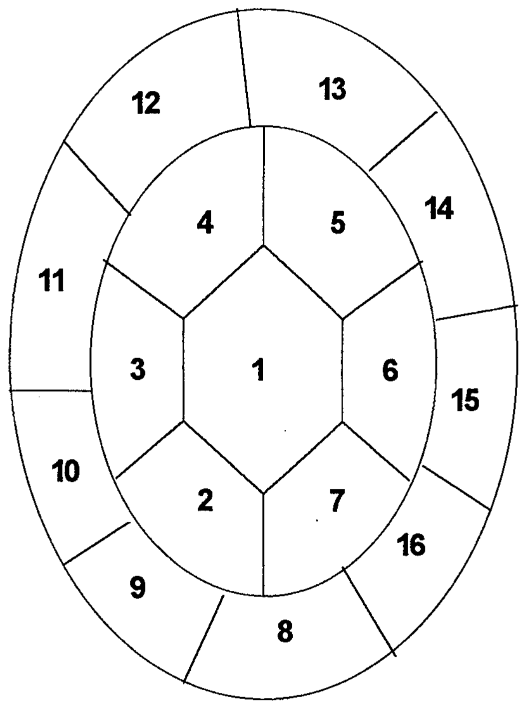

Figure 2.1. Individual Service Beam Coverage Pattern

2. Earth Segment

a. User Segment

GLOBALSTAR's user segment consists of hand-held, mobile, and fixed terminals [Ref. 6: p.22]. The hand-held unit, similar to a cellular phone, and mobile unit, similar to a vehicle-mounted cellular phone, will be dual mode. Dual mode implies that they can be used with existing terrestrial, cellular systems or with the GLOBALSTAR system. This inter-operability with existing cellular systems is cost effective when both systems use CDMA. The fixed terminals will be for GLOBALSTAR system use only.

User segments are frequency agile and operate to receive signals in the S-Band, 2483.5 - 2500.0 MHz (a 16.5 MHz channel) and transmit on the L-Band, 1610.0 - 1626.5 MHz (a 16.5 MHz channel) [Ref. 6: p.13]. They use a variable rate encoding technique to provide data rates of 1.2 to 9.6 kbps [Ref. 2: p.122]. Variable rate encoding transmits 4.8 kbps when a voice signal is present but reduces the rate to 1.2 kbps when there are pauses in the conversation to minimize interchannel interference. A data rate of 9.6 kbps will be available in the future to provide toll quality service.

b. Gateways

GLOBALSTAR will utilize gateway earth terminals as its traffic interface between satellites and the existing terrestrial telecommunications networks [Ref. 2: p.104]. There are two basic kinds of gateways: network coordination gateways (NCG) and standard gateways. The NCG's will be used for both traffic interface and for call set-up, coordination, and termination. The standard gateway will serve only as a traffic interface.

The gateways contain radio frequency (RF) frontends to establish uplink and downlink communications with the satellites. The uplink (part of the forward link) operates in the C-Band, 5025.0 - 5225.0 MHz, with eight sub-bands. These sub-bands utilize LHCP and RHCP polarizations yielding a total of 16 channels each with a BW of 16.5 MHz, which for conciseness will be described as 16 - 16.5 MHz BW channels. The downlink (part of the reverse link) operates in the C-Band, 6875.0 - 7075.0 MHz, with eight sub-bands. They also utilize dual polarizations to provide 16 - 16.5 MHz BW channels.

3. Communications Links

a. General

The CDMA design utilizes a combination of frequency division, pseudorandom code division, and orthogonal signal multiple access. Frequency division divides each 16.5 MHz channel into 13 - 1.23 MHz channels [Ref. 6: p.20]. Pseudorandom code division spreads the signals' spectra over the 1.23 MHz channel. Orthogonal signal multiple access minimizes inter-signal interference and allows mobile stations to distinguish spread signals.

b. Forward Link

The forward link consists of a signal broadcast from a gateway, received by the satellite, and then re-broadcast by the satellite to the mobile station. The component links are referred to as the forward feeder link (gateway-to-satellite) and the forward service link (satellite-to-mobile station). The forward feeder link is in the C-Band (one of the 16 - 16.5 MHz channels), and the forward service link is in the S-Band (a 16.5 MHz channel).

As Fig. 2.2 shows, the input speech signal is digitized and fed into a variable rate speech coder [Ref. 7: p.539]. Next, convolutional encoding with a rate of one half and constraint length of nine is used to provide error detection and correction. The encoded symbols are then block interleaved to combat fast fading and scrambled with a user addressed long code pseudorandom-noise (PN) sequence [Ref. 2: Appendix 5, p.16]. Scrambling with this PN sequence provides privacy and an address for the signal being delivered to the mobile station. The last part of the bi-phase modulation section is Walsh covering, exclusive-ORing the scrambled, encoded signal with a row of a dimension-128 Hadamard matrix. Walsh covering provides 128 possible orthogonal signals in each 1.23 MHz channel, ensures nearly perfect isolation between multiple signals transmitted by the same satellite beam antenna, and allows the mobile station receiver to distinguish different signals.

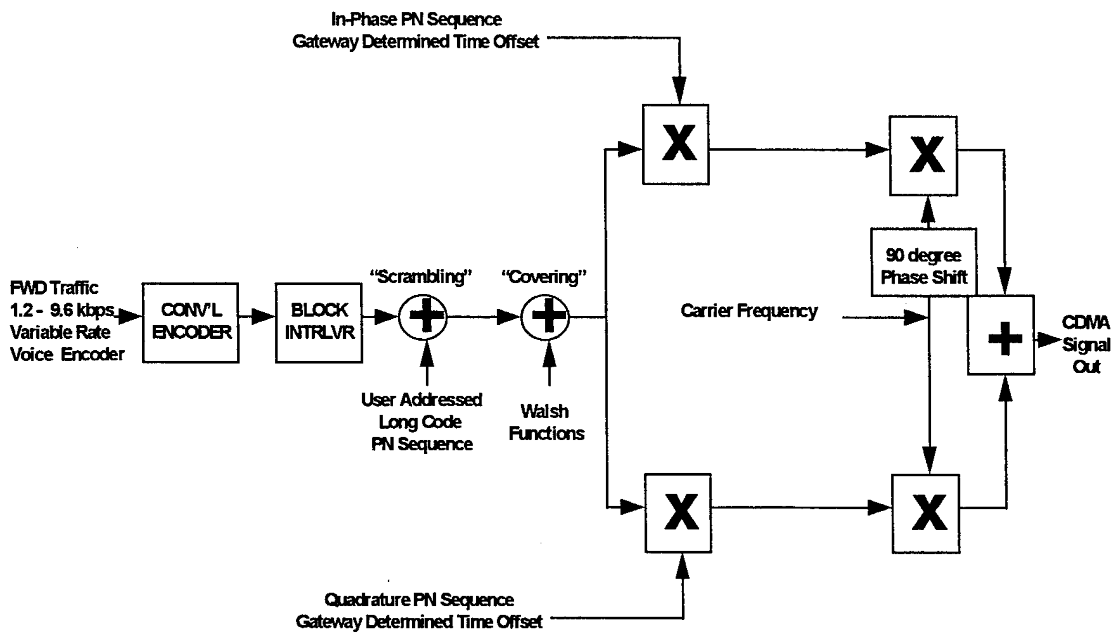

Figure 2.2. CDMA Forward Link Block Diagram

After Walsh covering the signal is quadri-phase modulated by a pair of identical PN codes. All gateways share a quadrature pair of PN codes, but each gateway uses a different time offset from the basic code [Ref. 2: p.14]. The time offsets allow the mobile station to distinguish between different gateways. They also ensure minimal interference between gateways as the crosscorrelation functions will average to zero.

In summary, the forward link is (1) digitized and rate coded, (2) convolutionally encoded, (3) block interleaved, (4) bi-phase scrambled with a user addressed long code PN sequence, (5) bi-phase modulated with 1 of 128 orthogonal Walsh functions, (6) quadri-phase modulated by a basic PN sequence with a gateway determined time offset, and (7) quadri-phase modulated by a carrier frequency. The user addressed long code PN sequence is used as an address for a mobile station. The Walsh functions provide orthogonality and allow the mobile station to receive its signal with minimal interference from other signals sent by the same gateway. The basic quadrature PN sequence with gateway assigned time offset allows the mobile station to distinguish between different gateways.

c. Reverse Link

The reverse link consists of a signal broadcast from a mobile station, received by the satellite, and then re-broadcast by the satellite to the gateway. The component links are referred to as the reverse service link (mobile-to-satellite) and the reverse feeder link (satellite-to-gateway). The reverse service link is in the L-Band (a 16.5 MHz BW channel), and the reverse feeder link is in the C-Band (one of 16 - 16.5 MHz BW channel).

As Fig. 2.3 shows, the input speech signal is digitized and fed into a variable speech encoder. Next, convolutional coding with a rate of one third and constraint length of nine is used for error correcting and detecting. The coded information is block interleaved over a 20 ms interval. The coded, interleaved symbols are then block coded using a 64-ary orthogonal modulator [Ref. 7: p.541].

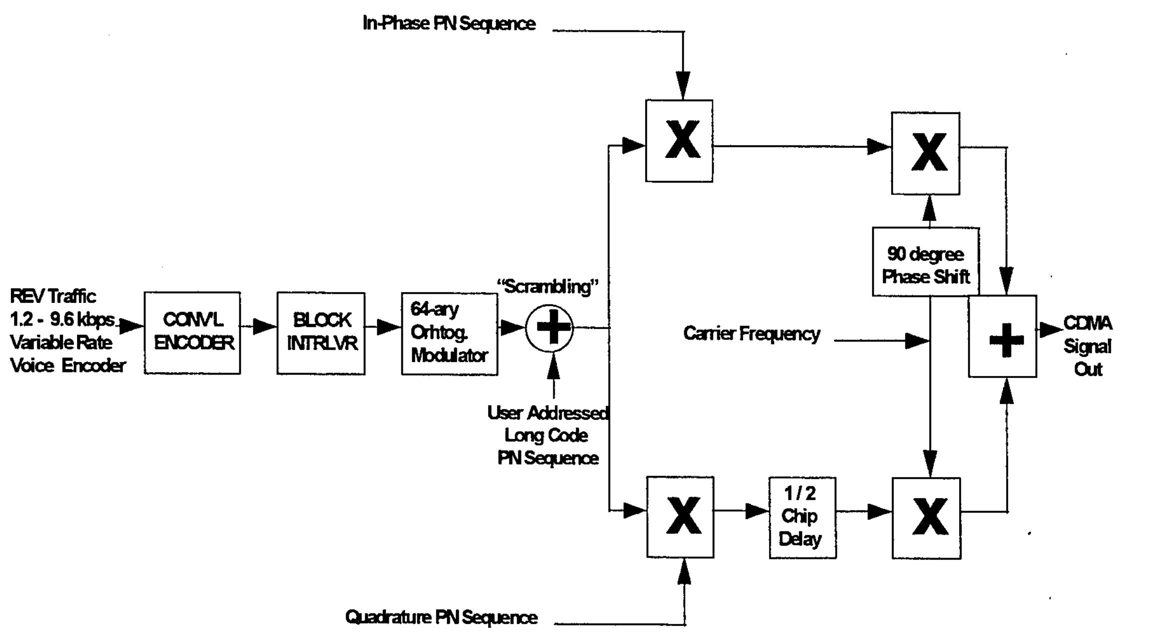

Figure 2.3. CDMA Reverse Link Block Diagram

The orthogonal modulator is shown in Fig. 2.4. The clock is initially assumed to be reset and will clock all counters simultaneously [Ref. 7: p.542]. The outputs of the clock and counter stages are multiplied by the elements of the index, $u_6u_5u_4u_3u_2u_1$, to form six weighted bits. The index is a binary vector of six elements based on six sequential symbols from the block interleaver. The six weighted bit streams are modulo-2 summed. When the clock is clocked 64 times, a 64 element bit stream is produced. This 64 element bit stream is a row of a Hadamard matrix that corresponds to the block of the interleaved, data based, index vector. This use of the Walsh function on the reverse link is a means of obtaining 64-ary modulation, different than the forward link's use of Walsh functions to obtain orthogonal signals [Ref. 2: Appendix 5, p.19].

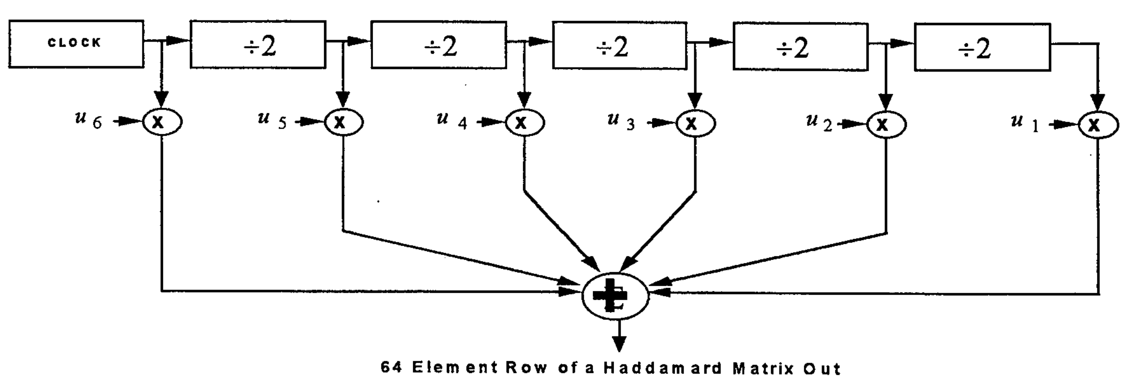

Figure 2.4. 64-ary Orthogonal Modulator Diagram

The output of the 64-ary modulator is scrambled and spread by the use of a long PN code with user address determined code phase [Ref. 7: p.542]. The scrambled data stream is spread further by simultaneously spreading the data in quadrature with two short length PN sequences. Last, the resulting quadrature channels are applied to an offset-QPSK modulator for filtering and mixing up to output carrier frequency.

In summary, the reverse link is (1) digitized and rate coded, (2) convolutionally encoded, (3) block interleaved, (4) bi-phase modulated by the Walsh code, (5) bi-phase modulated by a long PN code with a user address determined time offset, (6) quadri-phase modulated by a pair of PN codes, and (7) offset quadri-phase modulated by a carrier frequency.

B. CAPACITY STUDY

1. Hard Capacity Limit

The hard capacity limit is the maximum number of full duplex voice channels that a satellite can possibly support. This limit is based on all stations, gateways, mobile-units, and satellite transponders having sufficient power to deliver all signals with acceptable bit error probability. It also assumes that all available channels on all links have enough mobile users and gateways to completely utilize them.

Each satellite has 16 - 16.5 MHz BW channels available on the feeder links, gateway-to-satellite, and satellite-to-gateway. The service links consist of a single 16.5 MHz BW channel. However, the satellite footprint consists of 16 beams. Through the use of CDMA, the 16.5 MHz channel can be reused on each of the multiple beam antennas per satellite [Ref. 6: p.20]. Thus, GLOBALSTAR has a total of 16 - 16.5 MHz channels on both segments of its forward and reverse links.

The use of spread spectrum CDMA takes each signal and spreads it over a 1.23 MHz channel. A 16.5 MHz channel provides for a total of 13 - 1.23 MHz sub-channels.

Within each 1.23 MHz channel, signals are demodulated by use of their user addressed long code PN sequence. However, the maximum capacity is based upon the number of orthogonal signals per sub-channel. There are 128 possible orthogonal signals per sub-channel. This number corresponds to the forward link Walsh covering which uses a dimension-128 Hadamard matrix. However, only 125 are available for full duplex calls as one is required for a pilot channel, one for a paging channel, and one for a synchronization channel.

Therefore, the hard capacity limit, L_H, is given by

$$L_H = \left(\frac{125\ signals}{1.23\ MHz\ BW\ channel}\right)\left(\frac{13 - 1.23\ MHz\ BW\ channel}{16.5\ MHz\ BW\ channel}\right)\left(\frac{16 - 16.5\ MHz\ BW\ Beams}{Satellite}\right) \tag{2.1}$$

Equation (2.1) is evaluated to obtain L_H = 26,000 orthogonal signals/satellite or 26,000 full duplex calls per satellite. This many full duplex calls per satellite is not realizable. As can be seen from Fig. 2.5, one satellite's footprint never completely covers a region of possible users. Thus, there will be beams in the footprint that have no use for their allotted power and may be shut-off. This flexibility amongst the beams allows other beams to actually obtain their hard capacity beam limit, $L_{H,B}$. $L_{H,B}$ for GLOBALSTAR is 1625 full duplex calls per beam.

Next, the beam overlap in Fig. 2.5 must be considered. For certain systems, beam overlap is not permitted. However, with GLOBALSTAR's CDMA plan, overlap is permitted and exploited to increase capacity for two main reasons [Ref. 2: Appendix 5, p.10]. First, two satellites can actually produce roughly twice the signal strength at the earth. Second, the

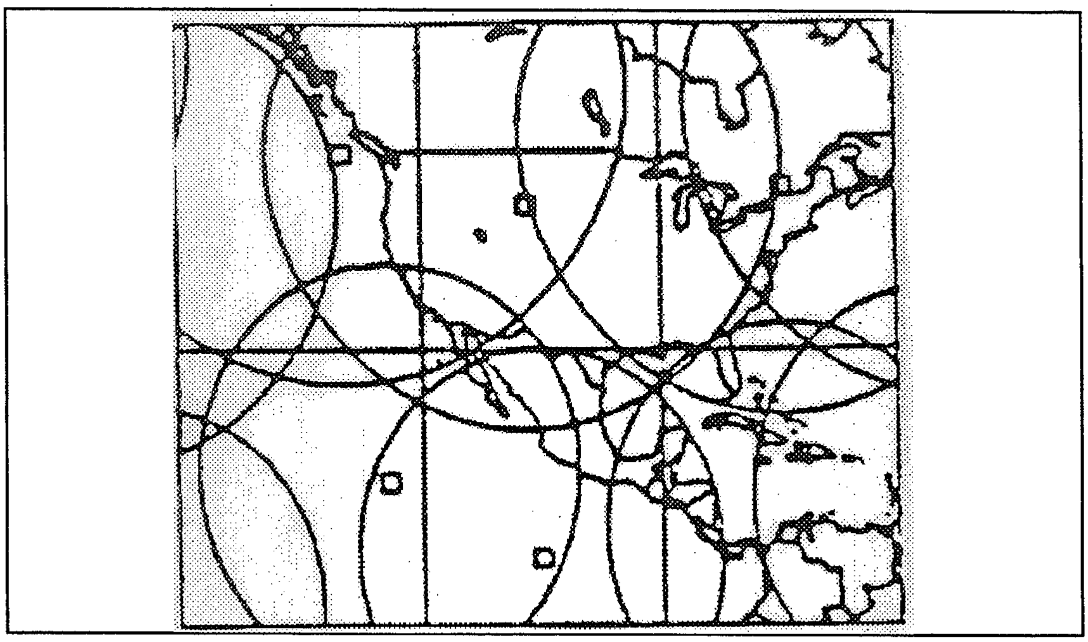

Figure 2.5. Maximum GLOBALSTAR Satellite Coverage Over CONUS From Ref. [2]

entire RF power budget can be directed into single spot beams in areas of high usage resulting in a significant increase in capacity, approaching $L_{H,B}$.

To estimate the maximum number of calls possible over a given geographic area, consider the continental United States (CONUS) in Fig. 2.5. Assume power in all satellites involved is allocated just to those beams focusing on the CONUS, and assume that users are evenly and heavily distributed throughout the entire region. The figure shows that the maximum number of satellites in this configuration will be four. The four satellites will be able to allocate 39%, 20%, 15%, and 4% of their total L_H. Thus, four satellites coordinate coverage over the CONUS to provide 78% of L_H, 20280 full duplex calls.

No data was given in Ref. 6 as to the GLOBALSTAR capacity for CONUS using the 16 beam configuration. However, the original GLOBALSTAR configuration proposed a six beam footprint and supplied data for four satellite coverage of CONUS: 7600 full duplex voice channels [Ref. 2: p.12]. Substituting 6 - 16.5 MHz BW channels/satellite into (2.1), we get $L_H = 9750$. Further, using the 78% approximation yields 7605 full duplex voice channels for the six beam configuration.

2. Outage Probability

Outage probability is the probability that a call will be dropped from the system or blocked from connection with the system . Outage probability, P_{out}, is defined for systems utilizing spread spectrum CDMA technology such as GLOBALSTAR . The following derivation follows the development of Vitebri [Ref. 8: p.203].

To begin, we first assume that there are k_u perfectly power-controlled, Poisson distributed users in one satellite beam's footprint. Given this assumption, all signals reach the satellite with the same energy and, hence, the same interference contribution to all other signals. The total power received, with bit energies E_b, data rates R, background one-sided noise power spectral density N_o, and total occupied bandwidth W for all users is given by

$$Total\ Power = \sum_{i=1}^{k_u} v_i E_b R + N_o W \tag{2.2}$$

where v_i is a binary random variable which indicates whether or not the i^{th} user is active. This random variable is related to ρ, the activity factor, defined as the ratio of time during which the user's signal is present. Therefore,

$$\rho \equiv P[v_i = 1] = 1 - P[v_i = 0]. \tag{2.3}$$

Assume that the desired user's power is denoted by subscript 1. The average noise-plus-interference power I_oW is

$$I_o W = \sum_{i=2}^{k_u} v_i E_b R + N_o W. \tag{2.4}$$

It is necessary, for dynamic range limitations on the multiple access receiver of bandwidth W, to limit the total received noise-plus-interference-power-to-background-noise-power to

$$\frac{I_o W}{N_o W} \leq \frac{1}{\eta} \Rightarrow I_o W \leq \frac{N_o W}{\eta} \tag{2.5}$$

so that

$$I_o W - N_o W \leq N_o W \left(\frac{1}{\eta} - 1 \right) \tag{2.6}$$

where η is less than unity and is usually between 0.25 and 0.1. We now solve (2.5) for I_oW - N_oW to remove the random variable I_o from future equations. This is a distinct deviation from Viterbi [Ref. 8: p.203] where the final result is obtained in terms of I_o. Combining (2.4) and (2.6), we get

$$\sum_{i=2}^{k_u} v_i \leq \frac{\left(W/R \right) \left(\frac{1}{\eta} - 1 \right)}{E_b / N_o} \equiv S_o' . \tag{2.7}$$

When this condition is not met, the system is deemed in an outage condition. The upper bound of outage probability is found when the desired signal's power is included in the summation. Thus,

$$P_{out} = P\left[\sum_{i=2}^{k_u} v_i > S_o' \right] < P\left[\sum_{i=1}^{k_u} v_i > S_o' \right] \tag{2.8}$$

is the outage probability. The number of users in the system, k_u, is assumed to have a distribution given by the "Lost Calls Held" Poisson formula [Ref. 9: p.78]

$$P_{k_u} = \frac{\left(\lambda/\mu \right)^{k_u}}{k_u !} e^{-\left(\lambda/\mu \right)} \tag{2.9}$$

with average arrival rate from the entire system λ (calls/min), average call duration $1/\mu$ (min), and mean and variance both given by λ/μ. Now, consider the random variable

$$Z = \sum_{i=1}^{k_u} v_i \,. \tag{2.10}$$

The distribution of Z is best determined from its moment generating function

$$E\left[e^{sZ}\right] = E_{k_u}\left[\prod_{i=1}^{k_u} E_{\nu_i}\left[e^{s\nu_i}\right]\right] \tag{2.11}$$

where E[ ] is the expectation, E_{ku} [ ] is the expected value over k_u, and E_{vi} [ ] is the expected value over ν_i. From Stark and Woods [Ref. 10: p.200], (2.11) becomes

$$E\left[e^{sZ}\right] = E_{k_u}\left[\rho e^{s} + (1-\rho)\right]^{k_u} \,. \tag{2.12}$$

Finally, using Papoulis [Ref. 11: p.119], the expected value over k_u may be evaluated to give

$$E\left[e^{sZ}\right] = \exp\left[\frac{\lambda\rho}{\mu}\right]\left(e^{s} - 1\right) \,. \tag{2.13}$$

Equation (2.13) is the moment generating function of a Poisson random variable with mean and variance $\rho(\lambda/\mu)$. Hence, Z is Poisson, and the outage probability is bounded by the sum of the Poisson tail

$$P_{out} < e^{-\rho\lambda/\mu} \sum_{k=S_o'}^{\infty} (\rho\lambda/\mu)^k / k! \,. \tag{2.14}$$

Next, we not only consider the users in one beam's footprint but the interference contributed by users in other footprints as well. The average interference power of these other users is some fraction "f" of all of the power of users in the other cells. The other cell interference factor, f, has been determined to lie between 0.5 and 0.6 [Ref. 8: p.207] . Following Viterbi, we will model the interference effects by augmenting the in-cell users by this additional fraction [Ref. 8: p.207]. Thus, the effective number of total users in the system

$$k_u' = k_u(1 + f) \tag{2.15}$$

is Poisson with parameter $\rho(\lambda/\mu)(1+f)$. The outage probability is now upper bounded by

$$P_{out} < P\left[\sum_{i=1}^{k_u'} v_i > S_o'\right]. \tag{2.16}$$

One last modification must be made to the above assumptions before proceeding. Initially, it was assumed that all users were perfectly power-controlled. This is not, obviously, the case. Users will be controlled to a desired E_b/I_o where the received E_b/I_o level is modeled as a log-normal distribution with standard deviation experimentally determined to be 1.5 to 2.5 dB. This log-normal distribution comes about from the multi-path propagation conditions inherent in the system. Therefore, the bit energy E_{bi} received will vary from user to user with a log-normal distribution and is given by

$$E_{b_i} = \varepsilon_i E_{b_o} \tag{2.17}$$

where ϵ_i has a log-normal distribution and E_{bo} is a constant. The outage probability is now bounded by

$$P_{out} < P\left[Z' \equiv \sum_{i=1}^{k_u'} \varepsilon_i v_i > S_o' \right] . \tag{2.18}$$

Feller has shown that the distribution of Z' may be accurately approximated for large values of S_o' as a Gaussian random variable with mean $m_{Z'}$ and standard deviation $\sigma_{Z'}$ [Ref. 12: p.190]. Hence,

$$P_{out} = P\left[Z' > S_o' \right] = \frac{1}{\sqrt{2\pi}\,\sigma_{z'}} \int_{S_o'}^{\infty} e^{-\frac{(z'-m_{z'})^2}{2\sigma_{z'}^2}} dz' . \tag{2.19}$$

With $t = (z' - m_{Z'})/\sigma_{Z'}$ and $dt = dz'/\sigma_{Z'}$,

$$P_{out} = \frac{1}{\sqrt{2\pi}} \int_{\left(\frac{S_o' - m_{z'}}{\sigma_{z'}}\right)}^{\infty} e^{-t^2/2} dt . \tag{2.20}$$

Using the definition of the Q-Function, we obtain the outage probability as

$$P_{out} \approx Q\left[\frac{S_o^{'} - m_{z'}}{\sigma_{z'}}\right]. \tag{2.21}$$

Following Viterbi [Ref. 8: p. 211], we find the mean is

$$m_{z'} = E[Z'] = E\left[\sum_{i=1}^{k_u^{'}} \nu_i \varepsilon_i\right] = E\left[k_u^{'}\right]E[\nu_i]E[\varepsilon_i] \tag{2.22}$$

and

$$m_{z'} = (\lambda/\mu)(1+f)\rho E[\varepsilon_i]. \tag{2.23}$$

Again, following Viterbi [Ref. 8: p.211], the variance is

$$\sigma_{z'}^2 = Var[Z'] = Var\left[\sum_{i=1}^{k_u^{'}} \nu_i \varepsilon_i\right] = E\left[k_u^{'}\right]Var[\nu_i \varepsilon_i] + Var\left[k_u^{'}\right]\left[E[\nu_i \varepsilon_i]\right]^2 \tag{2.24}$$

and

$$\sigma_{z'}^2 = (\lambda/\mu)(1+f)\rho E\left[(\nu_i \varepsilon_i)^2\right] \tag{2.25}$$

where Var[ ] is the variance of a random variable. But k_u' is Poisson, so

$$E\left[k_u'\right] = Var\left[k_u'\right] = (\lambda/\mu)(1+f) \tag{2.26}$$

and

$$E\left[(\nu_i \varepsilon_i)^2\right] = Var\left[\nu_i \varepsilon_i\right] + \left[E\left[\nu_i \varepsilon_i\right]\right]^2 . \tag{2.27}$$

Recall that the ϵ_i are log-normal random variables. Therefore, the

$$x_i = 10\log_{10}\left(\varepsilon_i Eb_o / N_o\right) \tag{2.28}$$

are normally distributed random variables of mean m_c dB and standard deviation σ_c dB. From (2.28), we find

$$\left(Eb_o / N_o\right)\varepsilon_i = 10^{x_i/10} = e^{\beta x_i} \tag{2.29}$$

with

$$\beta = \ln(10)/10. \tag{2.30}$$

Since x_i is normal, the n^{th} moment of ϵ_i is evaluated from

$$E\left[\varepsilon_i^n\right] = \left(Eb_o / N_o\right)^{-n} \int_{-\infty}^{\infty} e^{n\beta x_i} \frac{e^{\left[-(x_i - m_c)^2/2\sigma_c^2\right]}}{\sqrt{2\pi\sigma_c^2}} dx_i . \tag{2.31}$$

When evaluated, (2.31) becomes

$$E\left[\varepsilon_i^n\right] = \frac{\left(e^{\beta m_c}\right)^n}{\left(E_{b_o}/N_o\right)^n} e^{n^2(\beta\sigma_c)^2/2}. \tag{2.32}$$

However, E_{bo}/N_o is a constant corresponding to the mean received signal-to-noise ratio

$$E_{b_o}/N_o = e^{\beta m_c} = 10^{m_c/10}. \tag{2.33}$$

Substituting (2.33) into (2.32), we get

$$E\left[\varepsilon_i^n\right] = e^{n^2(\beta\sigma_c)^2/2}, \tag{2.34}$$

and (2.23) and (2.25) become

$$m_{z'} = (\lambda/\mu)(1+f)\rho e^{(\beta\sigma_c)^2/2} \tag{2.35}$$

and

$$\sigma_{z'}^2 = (\lambda/\mu)(1+f)\rho e^{2(\beta\sigma_c)^2}, \tag{2.36}$$

respectively. The Gaussian approximation of outage probability may now be written as

$$P_{out} \approx Q\left[\frac{S_o' - \rho(\lambda/\mu)(1+f)e^{(\beta\sigma_c)^2/2}}{\sqrt{\rho(\lambda/\mu)(1+f)e^{(\beta\sigma_c)^2}}}\right]. \tag{2.37}$$

For a consumer using the GLOBALSTAR system, the terms of greatest interest in (2.37) are λ, the call arrival rate into the system, and $1/\mu$, the average call duration. The consumer must have some feel for how the GLOBALSTAR LEO system could handle a heavy barrage of incoming calls as might be expected during an emergency situation or handle varied length calls where long, reliable connections may be necessary for DoD or emergency crews in crisis times. Therefore, in Fig. 2.6 and Fig. 2.7, the call arrival rate was held constant at 100 calls/min and the average call time was varied. In Fig. 2.8 and Fig. 2.9, call arrival rate was varied and average call time was held constant at three minutes. Other values used were either conservative in nature or in the middle of experimentally determined data. The voice activity factor is assumed to lie between 0.35 to 0.5 ; 0.5 was chosen here. For propagation law m=4 and log-normal shadowing standard deviation $\sigma \approx 8$, the other cell interference factor, f, lies between 0.5 and 0.6 [Ref. 8: p.207]; 0.55 was chosen as the middle of the range. As previously stated, σ_c, the standard deviation of the received bit energy is conservatively assumed to be 2.5 dB. GLOBALSTAR's desired E_{bo}/N_o is 3.5 dB [Ref. 2: Appendix 5, p.6]. The spread spectrum bandwidth available for links is 1.23 MHz per beam, and the average data rate is 4800 bps or 9600 bps for toll quality (future availability). Lastly, η has been experimentally determined to be 0.1 [Ref. 8: p.206]. The MATLAB code for generating these figures may be found in Appendix A.

The results illustrated in Figs. 2.6 through 2.9 will be discussed in Chap. IV when they can be compared to the results obtained for the IRIDIUM system in the next chapter.

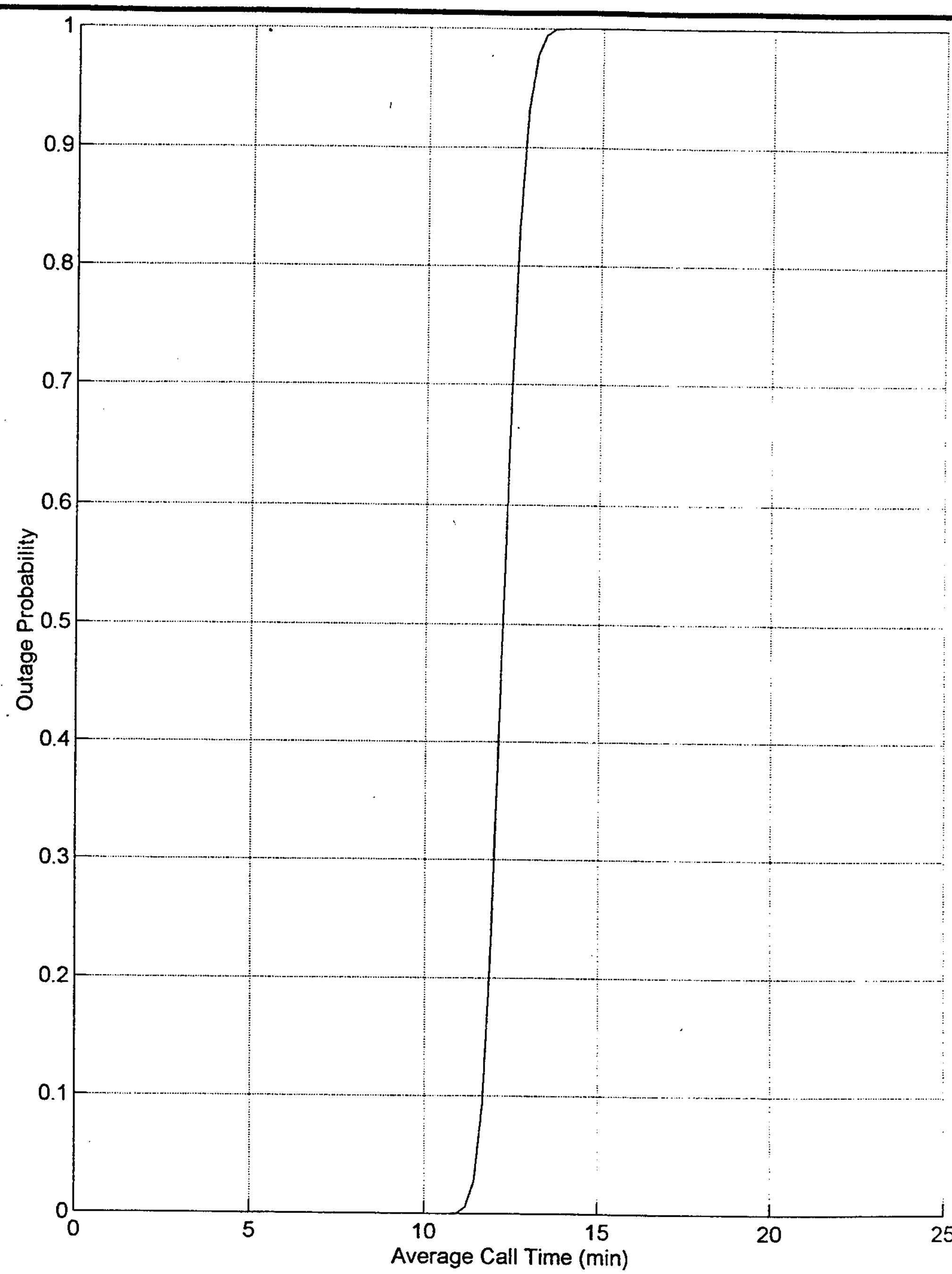

Figure 2.6 Outage Probability versus Average Call Time
(Call Arrival Rate = 100 calls/min and Data Rate = 4800 bps)

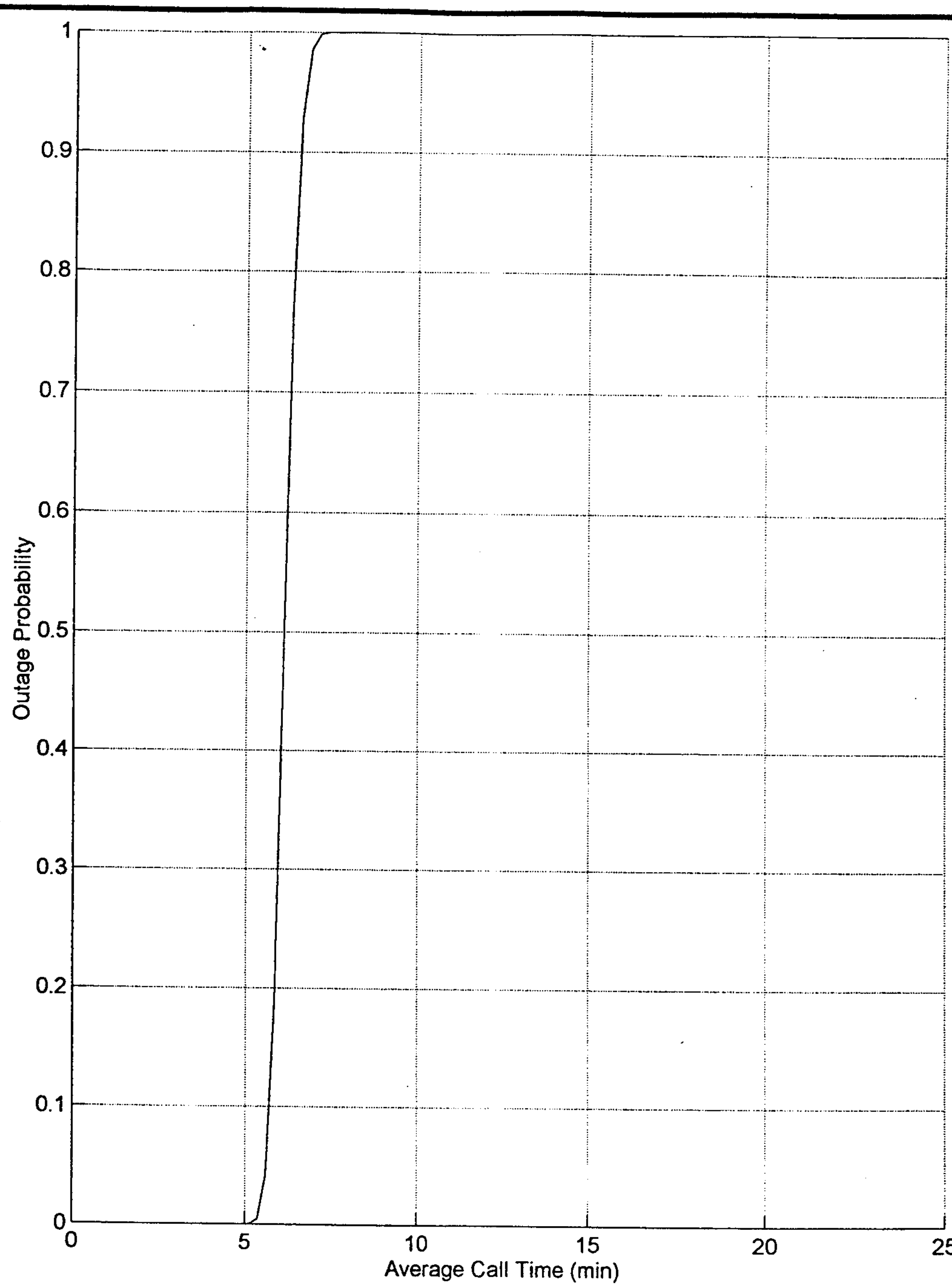

Figure 2.7 Outage Probability versus Average Call Time
(Call Arrival Rate = 100 calls/min and Data Rate = 9600 bps)

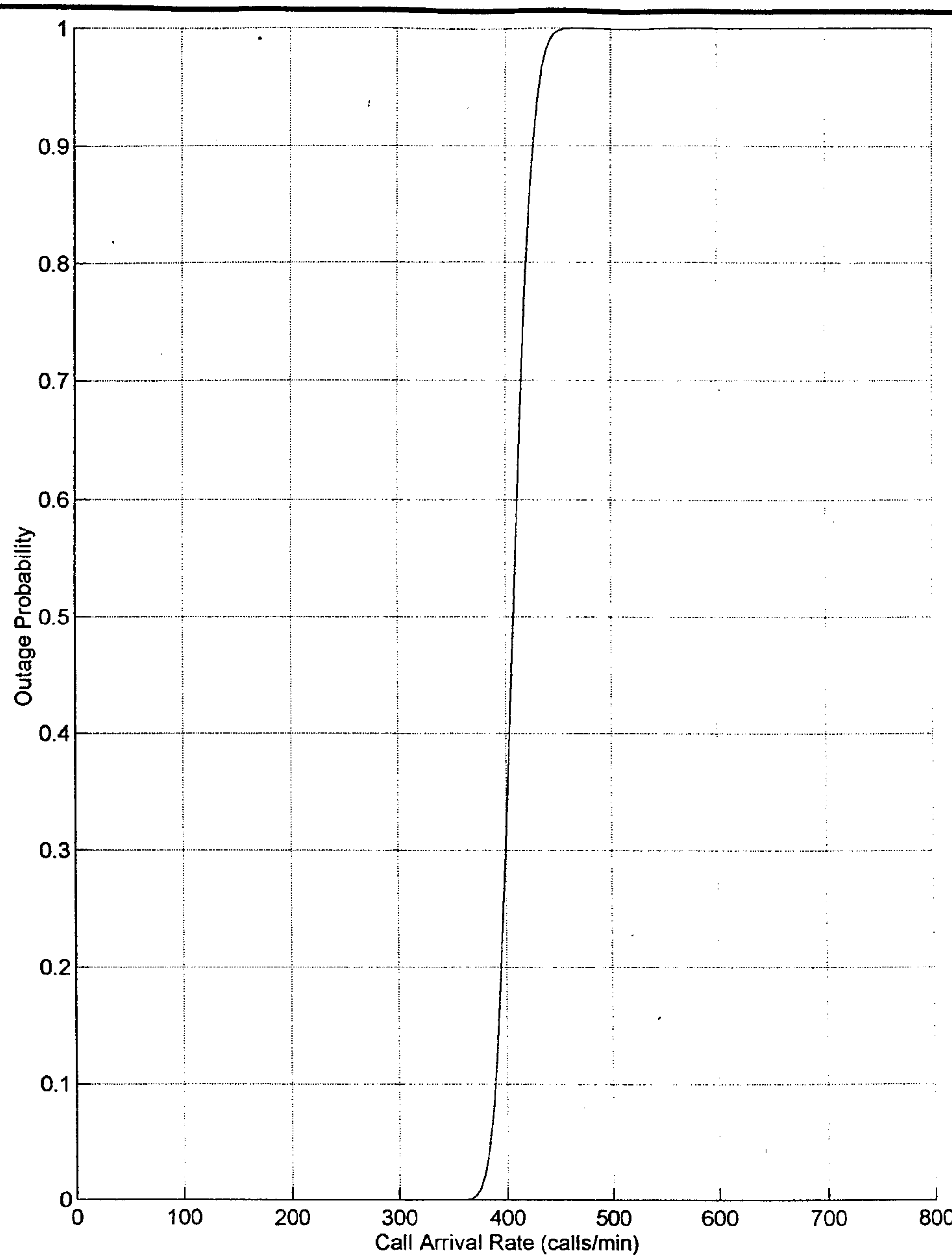

Figure 2.8 Outage Probability versus Call Arrival Rate
(Average Call Time = 3 min/call and Data Rate = 4800 bps)

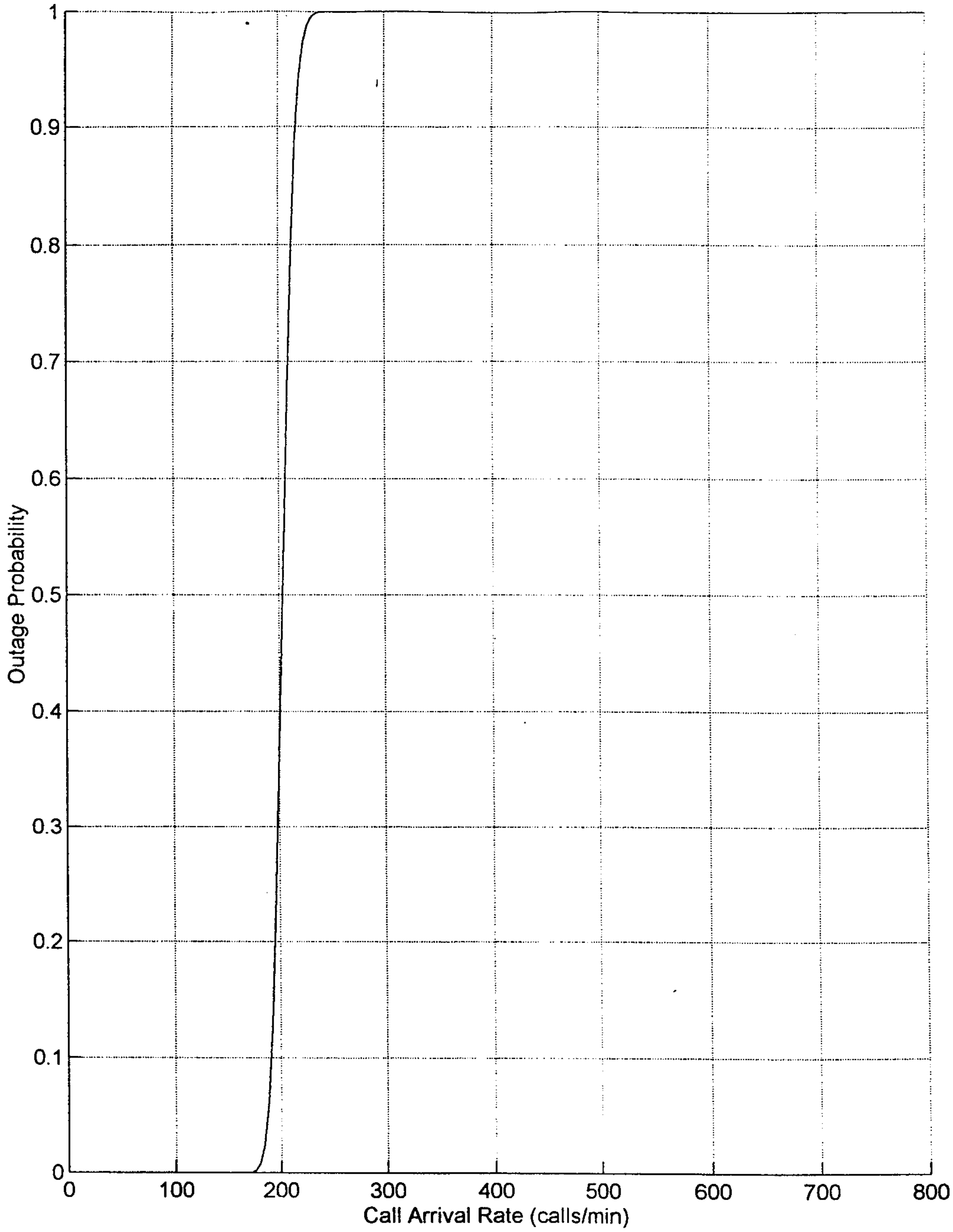

Figure 2.9 Outage Probability versus Call Arrival Rate
(Average Call Time = 3 min/call and Data Rate = 9600 bps)

III. IRIDIUM

A. SYSTEM DESCRIPTION

1. Space Segment

The IRIDIUM LEO satellite system will use a constellation of 66 non-geostationary satellites [Ref. 13: p.2]. These 66 operational satellites will be in six orbital planes, 11 satellites per plane, and at an altitude of 780.0 kilometers (484.7 statute miles). The inclination of the orbital planes is 86.4 degrees, the separation between the planes is 45 degrees, and the active arc is 360 degrees [Ref. 13: p.22].

The IRIDIUM satellites employ a complex myriad of beam technology and communications crosslinks. The satellites will receive a signal from a gateway station, an IRIDIUM subscriber unit, or another satellite. These satellite crosslinks represent a dramatic departure from the GLOBALSTAR design. An IRIDIUM satellite could receive a signal from a mobile user in Paris, use satellite crosslinks to transmit the signal across the Atlantic Ocean, and then have a satellite over CONUS send the signal directly down to a mobile user in New York City. A gateway station or the PSTN is not required for every call transmission (a gateway would still be involved with the call set-up and billing).

To facilitate the onboard processing and multi-directional signal transmissions, each satellite is equipped with three different sets of antennas. This design is much more complex than the GLOBALSTAR design. The Motorola SATCOM design engineers, however, feel that with production line assembly it is the most cost efficient design.

The first set of antennas are three multi-beam phased array antennas [Ref. 13: p.3]. These antennas create the 48 beam footprint on the earth's surface covering 15.3 million square kilometers (5.9 million square statute miles) shown in Fig. 3.1 [Ref. 13: p.23]. All of the beams operate in the L-Band with RHCP polarization. The second set of antennas are the four bottom mounted gateway antennas [Ref. 14: p.3]. For the downlink, these operate in the K-Band with LHCP polarization and, for the uplink, in the Ka-Band with RHCP polarizations. The last set of antennas are those that provide the satellite-to-satellite crosslinks. These operate in the K-Band with horizontal polarization [Ref. 14: p.9]. Each satellite may use these crosslinks to communicate with the satellite directly in front of and behind itself in the same orbital plane. The same satellite will also be able to communicate with the two nearest spacecraft in the adjacent co-rotating planes [Ref. 5: p.3].

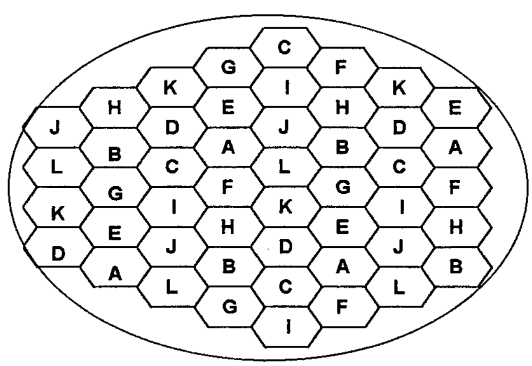

Figure 3.1. IRIDIUM's 48 Beam Satellite Footprint

2. Earth Segment

a. User Segment

IRIDIUM subscriber units (ISU) consist of hand-held portable units, vehicular mobile units, and transportable units [Ref. 15: p.37]. These units will all function in both terrestrial cellular mode and LEO satellite mode. The hand-held portable phone will emulate the existing Motorola cellular telephone interface, and the mobile unit will similarly emulate the Motorola mobile cellular phone. The transportable terminal may be temporarily installed in a building or other locations and may be viewed as a temporary "IRIDIUM phone booth."

The uplink and downlink service bands will operate in the L-Band , 1616.0 - 1626.5 MHz, with RHCP polarization. The frequency band is divided into 240 - 31.5 kHz bands and is reused in different cells by employing a 12 cell frequency reuse pattern, similar to terrestrial cellular designs. TDMA also permits frequency reuse within given cells on both the uplinks and downlinks.

b. Gateways

IRIDIUM will utilize gateways to control user access and interconnections to the PSTN [Ref. 15: p.34]. The design calls for multiple gateways to be distributed throughout the world and have at least two initially in the CONUS. There will also be one in eastern Canada and one in western Canada to coordinate with the two CONUS gateways to ensure coverage of all CONUS, Alaska, Hawaii, and all major US territories in the North American region. Gateways, which will be privately owned, will lease satellite capability from IRIDIUM.

The gateways will utilize two different frequency bands for uplinks and downlinks with the satellites [Ref. 14: p.29]. The uplink is in the Ka-Band, 29.1 - 29.3 GHz, and consists of 13 - 4.375 MHz channels. The downlink is in the K-Band, 19.4 - 19.6 GHz, and consists of 13 - 4.375 MHz channels as well. These links use forward error correction coding (rate 1/2), QPSK transmission of 6.25 Mbps coded data, and are not the limiting link in system capacity calculations.

The gateways contain three RF frontends [Ref. 15: p.84]. One establishes the uplink and downlink with the visible satellite for its region. The second frontend establishes the links with the satellite that will be active next, and the third one is a back-up to combat system failures.

3. Communications Links

a. General

The communications links in the IRIDIUM system are not succinctly described as forward and reverse links. While the gateway-satellite and ISU-satellite links consist of uplinks and downlinks, the satellite-to-satellite links add another factor to the link descriptions and allow multiple transmission paths. However, due to large bandwidths available to the satellite-to-satellite links (200 MHz) and to the gateway-satellite uplinks and downlinks (100 MHz), these links are not the limiting factors on system capacity. Rather, the satellite-to-ISU and ISU-to-satellite links, with limited 10.5 MHz BW, are the limiting capacity factor.

b. ISU-to-Satellite and Satellite-to-ISU Links

As was shown in Fig. 3.1, the IRIDIUM satellite's footprint for the ISU links contain 48 beams. The total coverage area of one satellite's footprint is 15.3 million square kilometers (5.9 million square statute miles) [Ref. 13: p.23].

As is shown in Fig. 3.2, the allotted L-Band, 1616.0 - 1626.5 MHz, is divided into 240 - 31.5 kHz channels with center frequencies of each channel spaced 41.67 kHz apart. There are also 2 - 255.0 kHz guard bands. With a 12 cell frequency reuse design, indicated in Figure 3.1 by the letters A-L, each cell is allotted and assigned 20 distinct channels.

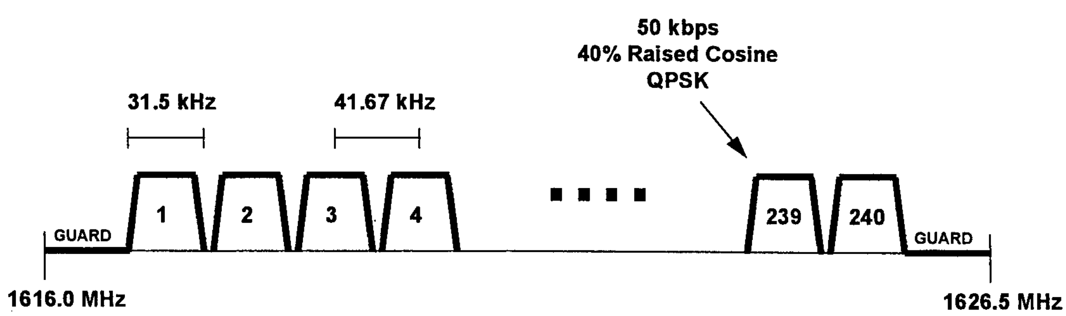

Figure 3.2. Frequency Plan for ISU-Satellite Uplinks/Downlinks

The ISU's use multiple rate forward error correction (the actual rate is still Motorola SATCOM proprietary) to provide 50 kbps coded data suitable for QPSK transmission [Ref. 14: p.9]. The QPSK signal uses 40% raised cosine pulse shaping requiring a null-to-null BW of 35.0 kHz. The 20 distinct frequency channels allocated per beam have a BW of 31.5 kHz. Therefore, only one ISU signal is permitted per channel.

The TDMA design chosen by Motorola SATCOM increases each cell's capacity by a factor of four. Figure 3.3 illustrates the TDMA format consisting of a framing slot, 4 uplink slots each 8.28 ms in duration, 4 downlink slots each 8.28 ms in duration, and distributed guard times to comprise the 90 ms frame. This configuration permits each transmit/receive beam to be visited up to four times per frame [Ref. 13: p.3].

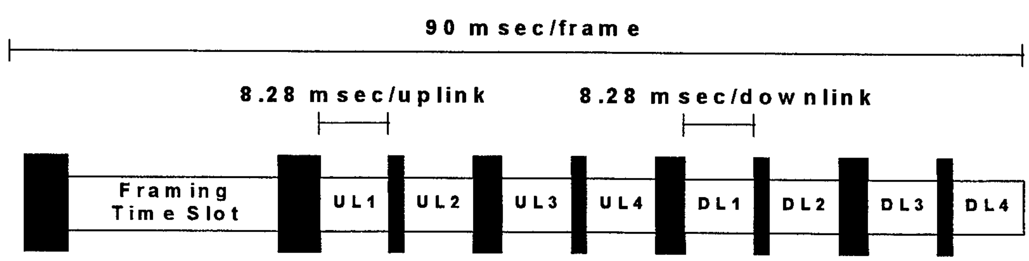

Figure 3.3. TDMA Frame Format

B. CAPACITY STUDY

1. Hard Capacity Limit

With the IRIDIUM design utilizing both TDMA and FDMA, multiple beam overlap is not permitted. Thus, when two or more satellites' earth coverage footprints converge, the satellites are programmed to "shut off" beams. With some beams shut off or all beams on, Motorola SATCOM proposes the onboard power system is capable of sustaining all possible channels on all available beams (the actual power requirement is still Motorola SATCOM proprietary). Therefore, a hard capacity limit per beam or per satellite will be the true capacity. To calculate the beam capacity, the number of frequency bands available must be known as must the transmission and receive times of each beam.

Each beam is allotted 20 - 31.5 kHz bands, and one band may be occupied by only one user at a time. Next, since there are four transmit and four receive times slots, each of the 20 bands may have four transmit and receive slots. In other words, assume users 1 - 20 are allotted 20 - 31.5 kHz bands. Similarly, users 21 - 40, 41 - 60, 61 - 80 are allotted the same 20 - 31.5 kHz bands. Users 1 - 20 will transmit during the first time slot and receive during the first receive slot. A similar pattern may be envisioned for the second, third, and fourth groups of users. Thus, the hard capacity beam limit, $L_{H,B}$, is given by

$$L_{H,B} = \left(\frac{1\ user}{31.5\ kHz\ band}\right)\left(\frac{20 - 31.5\ kHz\ bands}{beam}\right)\left(\frac{4\ time\ slots}{frame}\right) \tag{3.1}$$

Equation (3.1) is evaluated to obtain 80 users/beam.

This concept may easily be extended to find a satellite's hard capacity limit or the capacity for CONUS. There are 48 beams per satellite resulting in 80 x 48 = 3840 user channels/satellite (this corresponds to the capacity quoted in Ref. 13: p.23). Motorola SATCOM states that there will be 59 beams covering CONUS [Ref. 13: p.3]. This corresponds to 80 x 59 = 4720 user channels available for CONUS (this also corresponds to the capacity quoted in Ref. 13: p.23).

In summary of hard capacity limits, the maximum number of channels per any one beam is 80 channels. The maximum number per any one satellite is 3840 channels. Lastly, CONUS will have 4720 channels available for use.

2. Blocking Probability

The concept of capacity may now be expanded beyond hard capacity to include the probability of a call (user) being blocked from a full IRIDIUM system. A consumer must know the probability of success or failure for the event of turning on their ISU and a obtaining a channel for a call. The blocked calls lost model will be used because a user that cannot obtain a channel for a call has no queue to wait in. As with outage probability, the average length of the call and the call arrival rate are of paramount importance.

First, we define the two familiar variables λ and μ where λ is the call arrival rate (calls/min), $1/\mu$ is the average call time (min), and μ is the completed call rate (calls completed/min). Also note that when h channels are occupied (h is less than c, the total number of channels available for a caller), the probability of one busy channel completing a call is

$$P[1\ call\ completed\ during\ dt] = h\mu dt. \tag{3.2}$$

Next, Table 3.1 presents a clear picture of possible call scenarios and their related probabilities [Ref. 9, p.63]. Note that 0 < h=calls in the system < c=maximum calls available in system.

Customers at time t	Customers at time t + dt	Event during dt	Probability Expression
0	0	0 calls arrived	$(1-\lambda dt)P[0]$
1	0	1 call completed	$(\mu dt)P[1]$
h - 1	h	1 call arrived	$(\lambda dt)P[h-1]$
h	h	0 calls arr'd/comp'd	$(1-\lambda dt)[1-(h\mu)dt]P[h]$
h + 1	h	1 call completed	$[(h+1)\mu dt]P[h+1]$
c - 1	c	1 call arrived	$(\lambda dt)P[c-1]$
c	c	0 calls completed	$[(1-c)\mu dt]P[c]$

Table 3.1. Probability Expressions for Different Events Occurring During dt

The brief and classic derivation of the Erlang Loss Formula (Erlang B Formula) may be found in Beckman [Ref. 9: p.61]. The variables λ and μ, defined above, the probabilities of Table 3.1, and the referenced derivation yield the Erlang Loss Formula,

$$P_B = \frac{\frac{(\lambda/\mu)^c}{c!}}{\sum_{h=0}^{c} \frac{(\lambda/\mu)^h}{h!}}. \qquad (3.3)$$

For comparison to the GLOBALSTAR system and to keep a consistent comparison basis, values chosen will represent CONUS coverage. The total number of channels available will be c = 80. In Fig. 3.4, λ is held constant at 100 calls/sec; while in Fig. 3.5, $1/\mu$ is held constant at 3 minutes/call. Appendix B contains the MATLAB code for these figures.

The results illustrated in Fig. 3.4 and Fig. 3.5 will be discussed in the next chapter where they are compared to the results obtained for the GLOBALSTAR system.

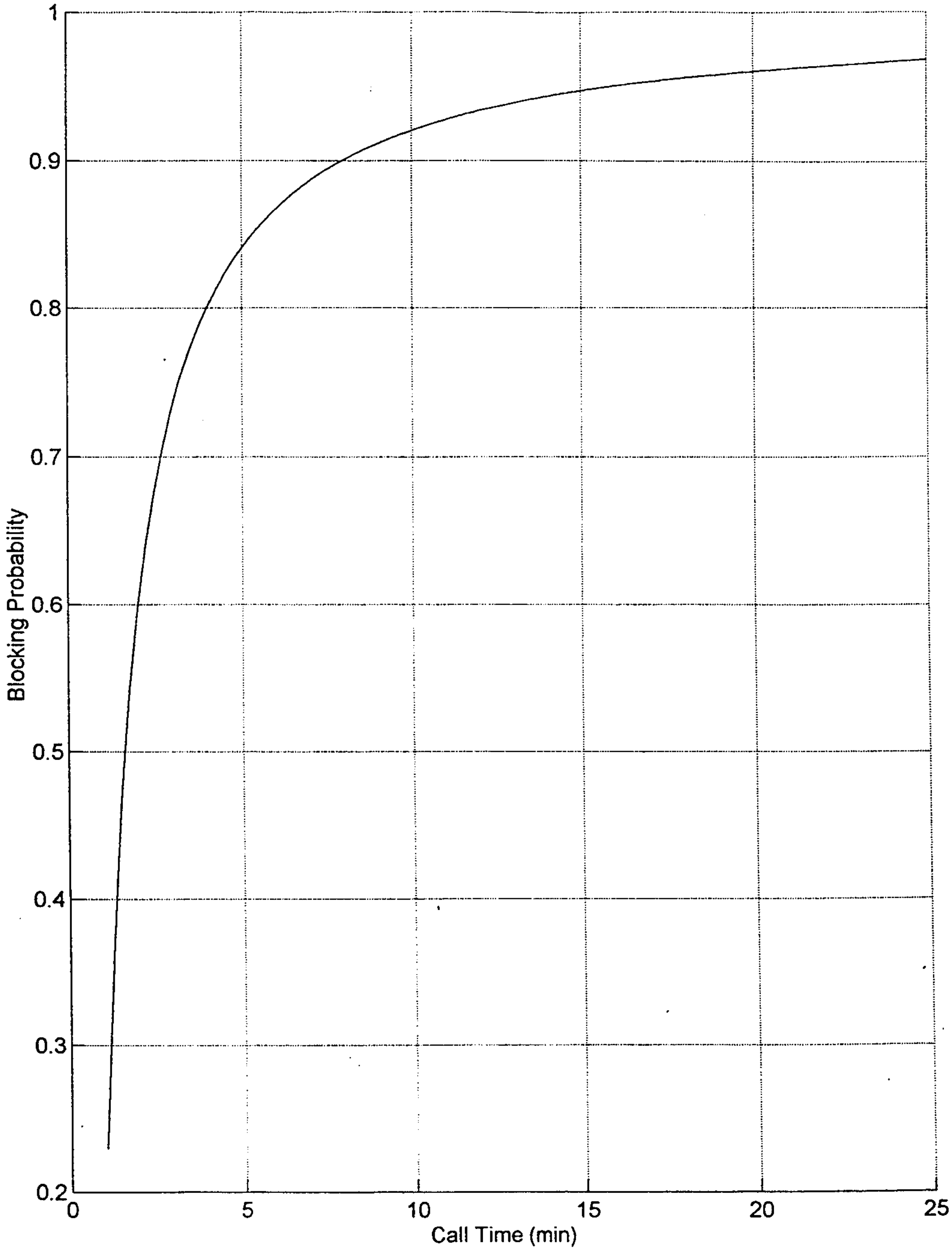

Figure 3.4 Blocking Probability versus Average Call Time
(Call Arrival Rate = 100 calls/min)

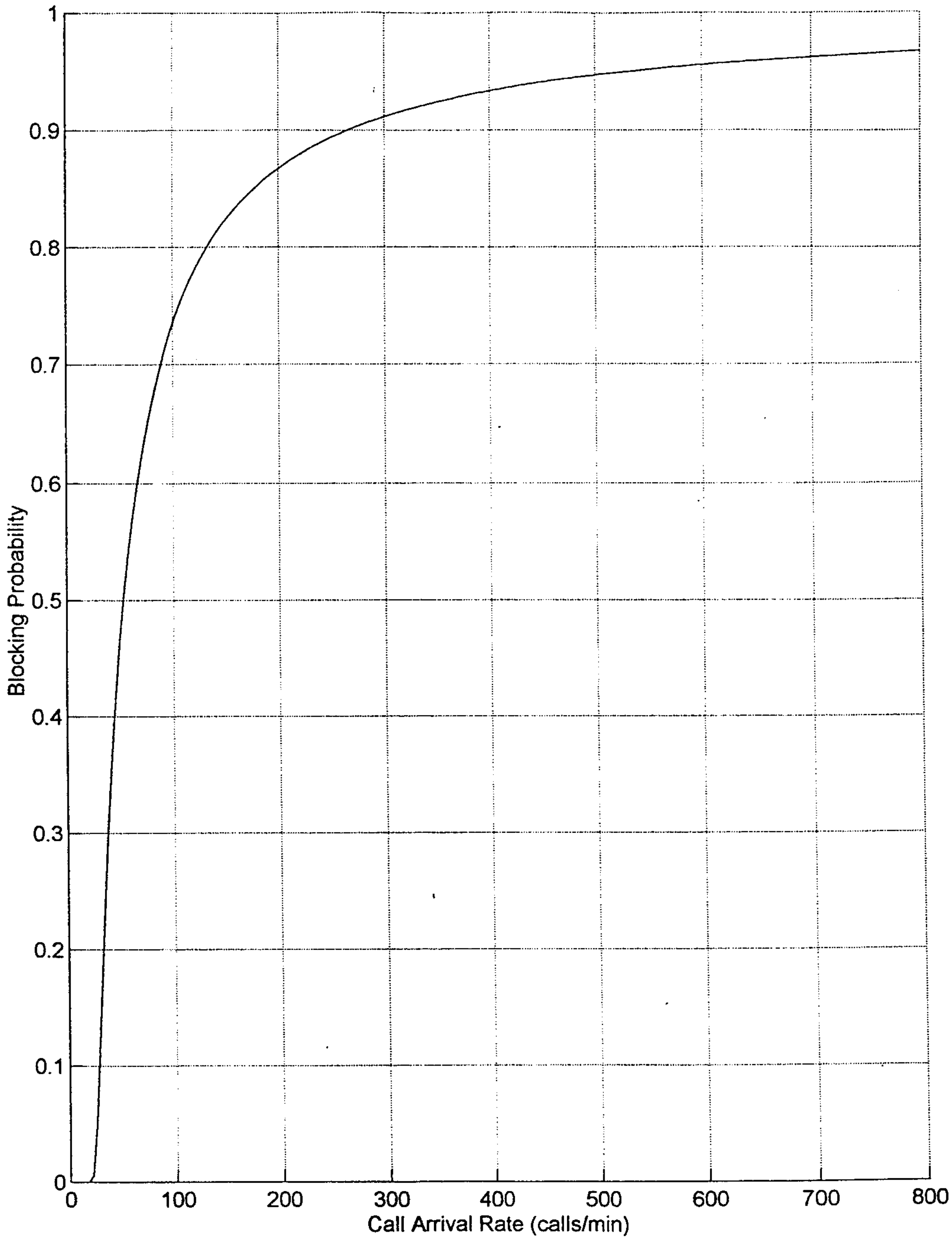

Figure 3.5 Blocking Probability versus Call Arrival Rate
(Average Call Time = 3 mins/call)

IV. DISCUSSION AND CONCLUSION

A. DISCUSSION

This thesis substantiates the claim that the DoD and private consumers must have a benchmark to be able to compare CDMA and TDMA/FDMA LEO satellite systems. It has shown how vastly different the link designs are and how vastly different capacity computations are. It also shows the necessity of further capacity studies of other existing and developing LEO satellites systems, such as TELEDESIC, ODYSSEY, and CONSTELLATION. These studies will become easier and clearer as more system design plans pass from proprietary to public domain, as the Federal Communications Commission assigns more specific bandwidths to each system, and as some operational experience is gained.

Hard capacity limits and hard capacity beam limits give the maximum possible capability of a LEO satellite or its associated beam. However, hard capacity limits are certainly more applicable to a TDMA/FDMA system where no beam overlap is permitted. For a CDMA system, where beam overlap is permitted and exploited, hard capacity beam limit is only partially relevant.

For a consumer, such as the DoD, to do a hard capacity limit study, the consumer must do the following. First, the consumer must pick a certain geographic region, such as the Persian Gulf or Washington, D.C., and analyze the channels from worst case and best case satellite footprints that a TDMA/FDMA system could produce. Next, the consumer must calculate the most and least number of beams and overlap scenarios that can cover these regions with a CDMA system. This will provide the best case and worst case capacities for CDMA versus TDMA/FDMA. As was shown in this thesis, a specific geographic area (such as CONUS) must be chosen and analyzed. The largest maximum number of channels need not be the deciding factor, though. If the DoD decided its needs can be met by a smaller capacity and less expensive LEO satellite system, this would prevent wasteful purchase of an expensive system with excessive bandwidth.

The other factor to be considered is the probability of success or failure of obtaining a channel for a call. The Erlang Loss formula used for blocking probabilities on the IRIDIUM system certainly paint a more bleak picture than the outage probability formula used for the GLOBALSTAR system. The TDMA/FDMA systems are limited by the number of frequency and time divisions available. The CDMA systems are, however, interference limited and can seemingly exceed Erlang capacities. At first glance, this may seem ludicrous. Can the number of users in a CDMA footprint actually exceed 128? With beam overlap, beam shut-off, re-allocation of power, and multi-path recombination, more than 128 users in a given footprint can actually obtain channels.

The limitations of a CDMA system are revealed by looking closely at (2.7) and (2.37). The spreading bandwidth W and dynamic range limitation of the receiver η are assumed to be constant as are σ_c, f, and ρ. However, if the bit energy-to-noise ratio E_b/N_o becomes too small, outage probability rises dramatically. Similarly, as the data rate R increases, as can be seen by comparing Fig. 2.6 to Fig. 2.7 and comparing Fig. 2.8 to Fig. 2.9, the outage probability also rises. As previously stated, the call arrival rate and the average call time are the most important factors to the consumer. When the call arrival rate λ

increases, GLOBALSTAR functions satisfactorily until about 400 calls/min (R= 4800 bits per second, bps) or about 200 calls/min (R= 9600 bps) are reached. The average call time presents similar limitations when it reaches 12 mins/call (R= 4800 bps) or about 6 mins/call (R=9600 bps) are reached.

Equation (3.3) does not have as many variables as (2.7) and (2.37), and the blockage probability appears to be quite limiting to the IRIDIUM system. The maximum number of channels per beam c is fixed by the TDMA/FDMA relationship. Call arrival rate λ and average call time μ present the only varying limitations to the system. IRIDIUM enters a call blocking situation when the call arrival rate reaches about 50 calls/min or the average call time reaches about 3 calls/min. These numbers are significantly less than those obtained for the equivalent parameters for the GLOBALSTAR system.

This study also assumed accurate link budgets and precise power allocations. Further studies must consider a CDMA system's ability to penetrate structures, such as hardened buildings, and survive varying atmospheric conditions, as might be present in war type scenarios. Interference caused by competing LEO satellite systems should also be examined. To date, the LEO system's applications have looked only at interference to and from existing communications systems.

B. CONCLUSION

In conclusion, this thesis has shown that GLOBALSTAR's CDMA LEO satellite system capacity for CONUS is five times that of IRIDIUM's. It has also shown that the probability of successfully obtaining a channel is much greater for GLOBALSTAR than for IRIDIUM given identical call arrival rates and average call times. The highest sustainable and successful call arrival rate for GLOBALSTAR is roughly 400 calls/min while that for IRIDIUM is 50 calls/min. The highest sustainable and successful call arrival rate for GLOBALSTAR is roughly 12 mins/call while that for IRIDIUM is 3 mins/call where success of LEO systems is considered to be outage probability and/or blocking probability less than 20%.

In this time of shrinking DoD budgets, a cost analysis is a necessity. If the smaller capacity IRIDIUM system can provide the number of DoD required channels at a more effective cost, it could prove the wise choice.

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APPENDIX A. MATLAB CODE: CALCULATING OUTAGE PROBABILITY

```
%LT Timothy M. Ciocco
%Code to Calculate Outage Probability for Data Rates of 4800 and 9600 bps
%W=bandwidth of the satellite beam links, R=data rates
%n=dynamic range limitation of multiple access receiver bandwidth W
%p=voice activity factor, f=other cell interference factor
%Sigma=standard deviation for the log-normal shadowing propagation model
%InvMhu=average call time, Lambda=average call arrival rate
W=1230000;
R1=4800;
R2=9600;
n=0.1;
EbOverNo=10^(0.35);
p=0.5;
f=.55;
Beta=(log(10))/10;
Sigma=10^(0.25);
InvMhu1=linspace(1,25,100);
Lambda1=100;
ko1=((W/R1)*((1/n)-1))/(EbOverNo);
ko2=((W/R2)*((1/n)-1))/(EbOverNo);
a=exp(((Beta*Sigma)^2)/2);
b=exp((Beta*Sigma)^2);
c=p*(1+f);
d1=sqrt(Lambda1.*InvMhu1);
e1=1./d1;
f=sqrt(c);
g11=((ko1.*e1)-(d1.*c*a))/(f*b);
g12=((ko2.*e1)-(d1.*c*a))/(f*b);
Z11=erfc(g11./sqrt(2))/2;
Z12=erfc(g12./sqrt(2))/2;
figure(1)
hold on
semilogy(InvMhu1,Z11)
grid
ylabel('Outage Probability')
xlabel('Average Call Time (min)')
figure(2)
hold on
semilogy(InvMhu1,Z12)
```

```
grid
ylabel('Outage Probability')
xlabel('Average Call Time (min)')
InvMhu2=3;
Lambda2=linspace(10,800,200);
d2=sqrt(Lambda2.*InvMhu2);
e2=1./d2;
g21=((ko1*e2)-(d2*c*a))/(f*b);
g22=((ko2*e2)-(d2*c*a))/(f*b);
Z21=erfc(g21/sqrt(2))/2;
Z22=erfc(g22/sqrt(2))/2;
figure(3)
hold on
semilogy(Lambda2,Z21)
grid
ylabel('Outage Probability')
xlabel('Call Arrival Rate (calls/min)')
figure(4)
hold on
semilogy(Lambda2,Z22)
grid
ylabel('Outage Probability')
xlabel('Call Arrival Rate (calls/min)')
ylabel('Log(Outage Probability)')
xlabel('Call Arrival Rate (calls/min)')
```

APPENDIX B. MATLAB CODE: CALCULATING BLOCKING PROBABILITY

```
%LT Timothy M. Ciocco
%Code to Calculate Blocking Probability
%InvMhu=average call time, Lambda=average call arrival rate
%c=maximum channels available per beam
InvMhu1=3;
Lambda1=linspace(1,800,200);
InvMhu2=linspace(1,25,200);
Lambda2=100;
Eta1=InvMhu1.*Lambda1;
Eta2=InvMhu2.*Lambda2;
c=80;
cfact=prod(1:c);
K1=(Eta1.^c)./cfact;
K2=(Eta2.^c)./cfact;
r=ones(1,81);
s=linspace(1,200,200);
L1=Eta1(r,s);
L2=Eta2(r,s);
d=linspace(0,80,81);
t=ones(1,200);
u=linspace(1,81,81);
M=d(t,u);
N=M';
O1=L1.^N;
O2=L2.^N;
d=[1 cumprod(1:c)];
P=d(t,u);
Q=P';
R1=O1./Q;
R2=O2./Q;
S1=sum(R1);
S2=sum(R2);
T1=K1./S1;
T2=K2./S2;
figure(1)
hold on
plot(Lambda1,T1)
grid
ylabel('Outage Probability')
```

```
xlabel('Call Arrival Rate (calls/min)')
figure(2)
hold on
plot(InvMhu2,T2)
grid
ylabel('Outage Probability')
xlabel('Call Time (min)')
```

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