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Estimates of Path Loss and Radiated Power for UHF Mobile-Satellite Systems

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This paper examines the satellite power requirements for land-mobile satellite systems, taking into account both shadow and multipath fading. Depending upon reliability objectives, present-day satellite capabilities will permit from 20 to 200 "(Advanced Mobile Phone Service) AMPS-like" circuits. Since satellite systems cost hundreds of millions of dollars, mobile-satellite telephony in a conventional sense would be expensive. Techniques are examined that in the far-term may permit a factor of 10 increase in capacity while still using moderate-size satellites.

I. INTRODUCTION

For the next decade or more the new 900-MHz land-mobile systems using cellular concepts will be introduced only in large cities. Any kind of nationwide service with full coverage will take many years. However, there are many nonurban applications where telephone service would be highly desirable, including service to vehicles along the nation's interstate highways, to rural residences currently without means of obtaining wire-line service, and to aircraft.[1-3] Communication from a satellite to small, portable terminals has been achieved, primarily demonstrating technical feasibility.[4,5] Other studies examined system costs assuming satellite payloads much larger than current capability, and paying little attention to propagation effects.[6-8] Although the monetary costs looked rather favorable, no such satellites or launch

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capabilities are expected in the near future. Here, the capacity-performance trade-offs are examined on realistic assumptions of near-term satellite capabilities, considering propagation conditions in some detail.

The issue of cost is not addressed except to mention that a modern, one-of-a-kind* satellite, in orbit, might be expected to cost well over 100 million dollars. At the same time the circuit capacity compared to a satellite system with large, fixed ground antennas will be smaller.

The procedure for the remainder of this paper is first to calculate an optimistic link budget based upon the assumption that there is a line-of-sight path between the satellite and the mobile system. Following this, estimates are made for the additional losses on the path due to obstructions near the mobile system; then an attempt is made to determine whether it is feasible to obtain sufficient radiated power in the satellite to make up these losses; finally, more spectrum- and power-efficient options are examined.

II. LINE-OF-SIGHT LINK BUDGET

The radiated power requirements on the satellite resources will be determined by working backwards from the mobile system. Assume for now frequency-division multiple access with a minimum carrier-to-noise ratio (CNR) of 10 dB in a 20-kHz bandwidth. These numbers are roughly consistent with the FM threshold and bandwidth requirements for present-day cellular mobile systems and would correspond to something that might be feasible in terms of a digital system in the future. These numbers imply 10 log C/kT = 53 dBW/K/Hz.

Since the mobile system can be driven in any direction, it is necessary that the antenna be omnidirectional in the azimuthal plane; however, since the satellite is never directly overhead, it is possible to form a conical beam in the elevation plane, and obtain a gain of about 6 dB. Assume a system noise temperature of 400 degrees for the mobile system. Although lower-noise receivers certainly could be built, limitations of man-made noise will prevent the effective use of lower-noise receivers; furthermore, the additional cost of ultra-low-noise receivers in mobile systems may be prohibitive. These two assumptions imply a $G/T = -20$. With these numbers the required illumination on the earth is -134 dBW/m^2. The path loss from the satellite to the mobile system calculates to 184 dB. As shown in Table I, the required Effective Isotropic Radiated Power (EIRP) per channel is 28 dBW at the satellite.

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* Multiple-satellite operation with frequency reuse would be practically impossible to achieve because the mobile antennas radiate essentially in an omnidirectional pattern, so there is no way to discriminate one satellite from another.

Table I—Link budget for a single mobile-satellite channel

Minimum CNR at mobile	10 dB
Noise bandwidth	20 kHz
Mobile receiver noise temperature	400°K
Antenna gain	6 dB
G/T	−20
Path loss	184 dB
Required satellite EIRP	28 dBW

It is possible to have an antenna with nearly a 15-foot diameter within the Space Shuttle. At 900 MHz such an antenna would provide an on-axis gain of 31 dB, while the gain at the edge of the country would be about 29 dB. We assume on the average that 30 dB of antenna gain is available, which implies a required radiated power per channel of −2 dBW for Continental United States (CONUS) coverage. The average RF power consistent with moderate-size satellites in the 1980s time frame is about 200W (+23 dBW), which implies 316 satellite-mobile channels.

III. ADDITIONAL PATH LOSSES

Excess path losses on land-mobile paths have been measured at numerous frequencies over a variety of paths worldwide. A great amount of data exists in the 800- to 900-MHz frequency band for land-mobile paths, but little data have been published on the losses over satellite-to-mobile paths. To estimate what losses might be expected, Fig. 1 shows a plot of the median path loss in excess of the free space path loss as measured for various base-station antenna heights,[9] plotted in terms of the elevation angle between the mobile and the base station. For distances of both 1 and 2 km from the base station, the points lie nearly on a straight line on semilog paper.

A recently published paper indicates that satellite path losses in the Denver area (elevation angle 32 degrees) range from 3 to 20 dB over line-of-sight.[10] The author's statistical description for excess path loss, corresponding to 50-percent large-scale coverage, estimates 9.8-dB excess path loss for a suburban environment with an elevation angle of 30 degrees. This value is in good agreement with the curve depicting a suburban environment plotted in Fig. 1. For more rural locations, satellite measurements would predict 5.3-dB excess path loss,[3] which tends to agree with the straight-line projection of the two data points taken 10 km distant from the high-elevation base stations. In all cases, due to the more favorable elevation angles, excess path losses are less severe on satellite-mobile paths compared to typical land-mobile paths, as long as the satellite is located at a longitude such that the slant range is not excessive.

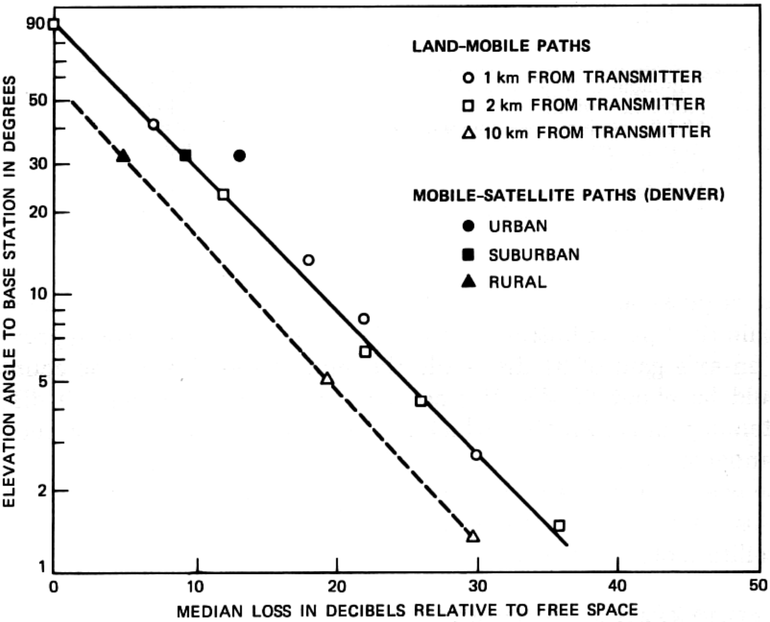


Fig. 1—Excess attenuation vs elevation angle at 900 MHz.

For a favorable satellite longitude and for most locations in the United States, the elevation angle to the satellite generally will be greater than 30 degrees and less than 60 degrees, indicating that it is reasonable to expect the median losses over free space to range from 3 to 10 dB, except possibly in urban areas where greater losses would be expected.

Data reported on land-mobile paths indicate that the distribution of the signal about the median is log normal with standard deviations ranging from 5 to 10 dB.[9] The log-normal distribution found in the land-mobile case arises from large-scale obstructions such as tall buildings and hills, which shadow the line-of-sight path. Intuitively, one might expect the variation of signal strength to be less severe on a satellite-mobile path, since typical elevation angles for a satellite are 30 degrees or more, where usual land-mobile paths have elevation angles more on the order of a degree or so. Based on the satellite data of Ref. 10, the variance of the log normal appears to be somewhat less for satellite paths than for land-mobile paths, but not dramatically so.

Figure 2 is a plot of what might be called the expected range of additional losses relative to free space based on available measured data.[10] It can be seen that high margins are required to provide service to approximately 99 percent of the regions of the country. Even assuming most regions of service interest are rural, margins in excess of 10 dB are often required. Furthermore, this would assume the propagation characteristics of the entire country are similar to those in the Denver area. A far safer approach (and perhaps more accurate) is to employ the surburban model to represent the small cities and towns where the bulk of the demand may be expected. In this case, to cover 90 percent of locations would require a signal approximately 16 dB above the line-of-sight value, and the value would increase to 21 dB for 99-percent coverage.

IV. MULTIPATH FADING

Another factor crucial to system performance is the effect of multipath fading. A line-of-sight component can be expected frequently on the satellite path. This component plus signal components, which scatter into the mobile antenna from nearby objects, produce a Rician signal distribution with significantly less fading than occurs with a Rayleigh distributed signal. Data on satellite paths confirm Rician-like signal statistics.[10] For example, level crossing rates can be an

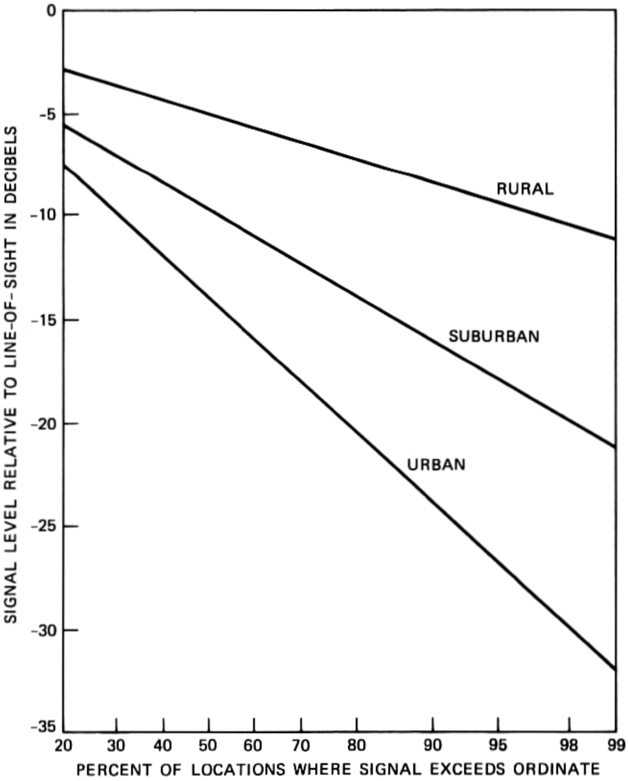


Fig. 2—Estimates of signal strength distribution on satellite-mobile paths.

order of magnitude or more lower compared to Rayleigh fading. Unfortunately, fading will be worst just at the wrong time—when the line-of-sight component is obscured and the received signal strength is low. Under these conditions the received signal can be assumed Rayleigh, and expected performance has been calculated.[11] In white Gaussian noise, a 10^{-3} Bit Error Rate (BER) is attained with an average energy per bit (E_b) 6.9 dB above the noise density (N_0) for biphase coherent phase shift keyed signals, while in the presence of Rayleigh fading an average E_b/N_0 of 24 dB is required. Spatially separated antennas whose signals are combined in phase can significantly reduce bit error rates. Figure 3 is a plot of BER vs E_b/N_0 for various numbers of diversity elements. For a 10^{-3} BER with three elements, E_b/N_0 per element drops to 7 dB, and with eight diversity elements it drops to 0 dB E_b/N_0. This somewhat surprising result is readily understood if one considers the eight elements as an antenna array, whose effective gain is 9 dB higher than a single element.

Space diversity works well on mobile systems, even with closely spaced elements ($<1\lambda$) that have highly correlated (0.5) signals.[9] However, space diversity cannot be achieved at the satellite because the arriving signal is essentially a plane wave, and extremely large separation of the satellite antennas would be required. A technique

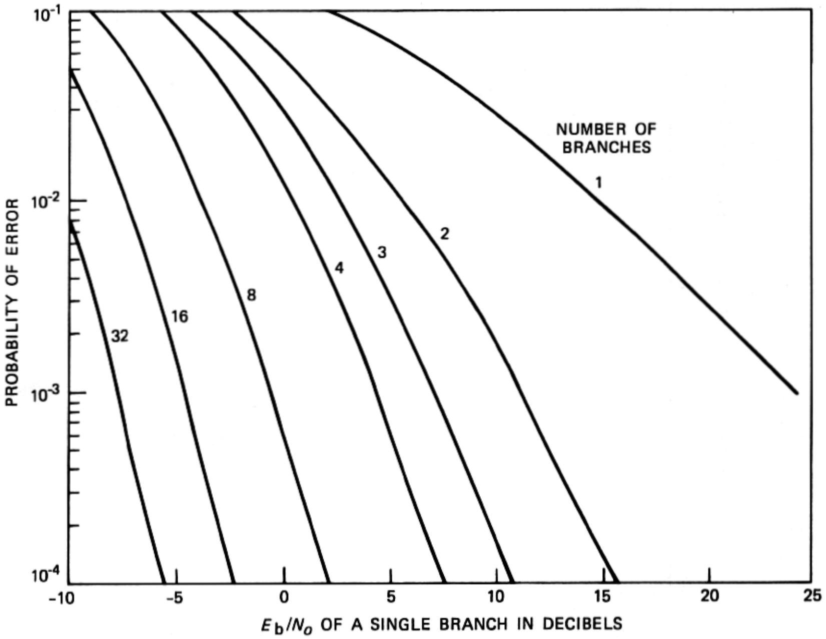


Fig. 3—Error probability of Two Coherent Phase Shift Keying (CPSK) with Rayleigh fading and diversity.

called retransmission diversity has been suggested for both analog[9] and digital transmission.[12] The idea is to transmit the conjugate phase of the received carrier on the same or a closely spaced carrier. By doing so, the signals from all mobile diversity branches will automatically arrive in phase at the satellite. In the original thinking for land-mobile system use, retransmissions would occur at the base stations, thereby simplifying the mobile system. In this instance, the only workable method is to place the retransmission apparatus at the mobile system. The analog scheme mentioned above would be very difficult to build, since the transmit and receive frequencies are closely spaced (<100 kHz), and the two signals differ in power by many tens of decibels. The digital techniques employ packet transmissions, and any hope for compatibility with cellular systems would be lost.

If the system were not constrained in bandwidth, then similar results could be obtained by employing frequency diversity channels. Beyond its obvious inefficiency, another drawback with frequency diversity is that the satellite must transmit the same signal on multiple channels, which requires more equipment and power. Another approach that achieves diversity advantage is to employ frequency hopping or spread-spectrum techniques.[13] This would eliminate the retransmission problem of space diversity but with possible reduction in capacity. An interesting possibility would be to combine space diversity with spread spectrum, using space-diversity mobile reception (because satellite power is at a premium) and spread-spectrum mobile transmission to combat Rayleigh fading.

Table II summarizes the per-channel power margins required for the various conditions of shadow and multipath fading, as discussed previously. We assume that a threshold of 10^{-3} BER is achieved with a calculated signal-to-noise ratio $(s/n) = 10$ dB. This allows 3.1 dB of implementation margin for filter and transmission line losses, antenna pointing errors, and nonideal detection equipment. The first observation from this table is that, without diversity, satellite-mobile com-

Table II—Power margin in excess of free space propagation, required to overcome shadow fading, and attain BER $\leqslant 10^{-3}$ in Rayleigh fading

	Margin Above Line-of-Sight (dB)								
	Urban Environment			Suburban Environment			Rural Environment		
Percent Coverage	No Diversity	2 Branch Diversity	8 Branch Diversity	No Diversity	2 Branch Diversity	8 Branch Diversity	No Diversity	2 Branch Diversity	8 Branch Diversity
50%	31	18	13	27	14	9	22	9	4
90%	41	28	23	33	20	15	25.5	12.5	7.5
99%	49	36	31	38	25	20	28	15	10

munications in dense urban areas is unachievable for the majority of locations. However, it is expected that cellular mobile systems will handle this traffic anyway. A margin of 15 dB with two-branch diversity would provide service to 99 percent of the rural locations, 60 percent of suburban locations, but only 25 percent of the urban locations.

Using Figs. 2 and 3, together with the link budget calculated in Table I, we can estimate quality of service for a given satellite EIRP. Table III gives the percentage of rural or suburban locations where performance exceeds the given BER for the indicated per-channel satellite transmitter power and for mobile systems with three diversity branches. Having only two diversity branches would increase power requirements by 3 to 5 dB, while having four diversity branches would lower the transmitter requirement by 2 to 3 dB, depending on the chosen threshold.

It is clear that typical satellite configurations are severely power limited when it comes to providing mobile services. Previously we saw that 316 circuits were available when all mobiles are line-of-sight. Permitting 15 dB of margin on each circuit reduces the capacity to only 10 circuits. Thus, ways of obtaining more EIRP must be found.

V. ADDITIONAL SATELLITE EIRP

It appears obvious that an approximate 10-dB signal-strength margin will be required for any reasonable satellite-mobile system. In Section II, calculations showed that 200W of RF power were required for 316 channels based on line-of-sight propagation. If only 32 channels were used, then an additional 10 dB of radiated power per channel would be available. However, cost estimates in this paper's introduction indicate that this would be almost certainly a cost-ineffective approach. On the other hand, the state-of-the-art cannot provide 2 kW of RF power in a satellite today; thus, we look to other means of effecting higher EIRP or its equivalent.

The question of efficient multiple-channel satellite transmission is

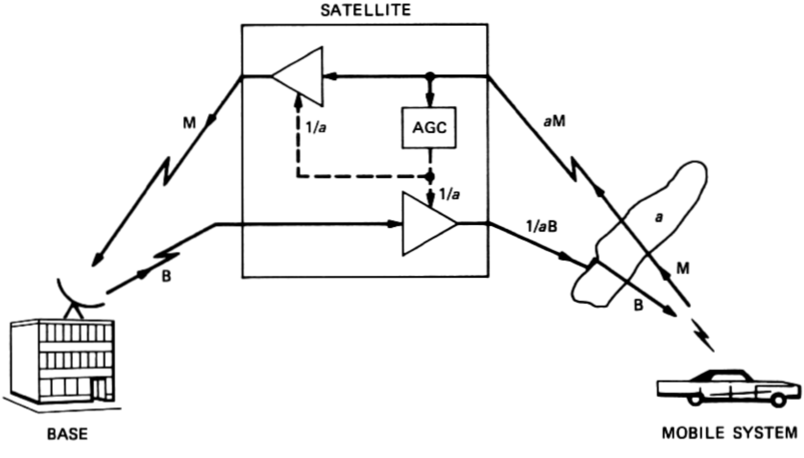
Table III—System performance for mobiles with three diversity branches

Percentage of Locations With BER Less Than Value	Satellite EIRP/Channel					
	33 dBW		38 dBW		43 dBW	
	Rural	Suburban	Rural	Suburban	Rural	Suburban
10^{-1}	>99.9	85	>99.9	92	>99.9	98
10^{-2}	96	45	>99.9	82	>99.9	91
10^{-3}	50	18	97	50	>99.9	78
10^{-4}	12	6	82	35	99.7	65

very complex. Given a total payload mass for power amplifiers and solar cells and batteries, what techniques best satisfy the system requirements? When there are only a few channels, a single-amplifier-per-channel operation is usually the simplest. For a large number of channels, the hardware complexity of a multitude of amplifiers and of multiplexing these RF signals onto an antenna feed necessitates another approach. Multicarrier operation (for analog or digital signals) simplifies the satellite tremendously but at a cost of power efficiency and potential intermodulation distortion. Transmitting digitally multiplexed signals from the satellite eliminates intermodulation and allows efficient high-power class C amplification, but requires that all signals be of the same power and that mobiles have high-speed Time-Division Multiple Access (TDMA) receivers. These issues as well as other transmission-efficient techniques are addressed in the following subsections.

5.1 Power control

We note that it is wasteful to provide all vehicles with the 10 dB or so margin to ensure that most of the vehicles have a signal above threshold. After all, some vehicles will be line-of-sight to the satellite and require substantially less power than those behind a mountain. Ideally, just enough power should be made available to ensure that each vehicle has a signal above threshold. This can be accomplished by using the technique illustrated in Fig. 4. The automatic gain-control signal is applied to a second transmitter carrying the message from the ground to the satellite. For illustration, the circuit is shown in the



AGC – AUTOMATIC GAIN CONTROL

Fig. 4—A technique to reduce shadow fading on mobile-satellite paths.

satellite, but it could be located at the earth station just as well if the satellite amplifier is linear. Because of the path delays, it could take a half-second or so to make a power adjustment. Therefore, the technique can be applied against slowly varying shadowing such has hills or large terrain features but not against multipath fading.

Recent work of Yeh and Schwarz allows us to calculate the total power expected from the sum of any number of log-normally distributed carriers.[14] Figure 5 contains plots that show the mean decibel value of a log-normal distribution that is derived from the sum of a number of log normals with the same mean (0 dB) and standard deviations ($\sigma = 2.5$, 5, 7.5 and 10 dB); these σ's correspond roughly to rural, suburban, urban, and dense urban environments. For example, the resultant of summing 100 carriers whose standard deviations are 5 dB is (approximately) a log normal whose mean is 22.5 dB. This means that providing a total peak RF power that is 22.5 dB above that of a single carrier would satisfy the power demand 50 percent of

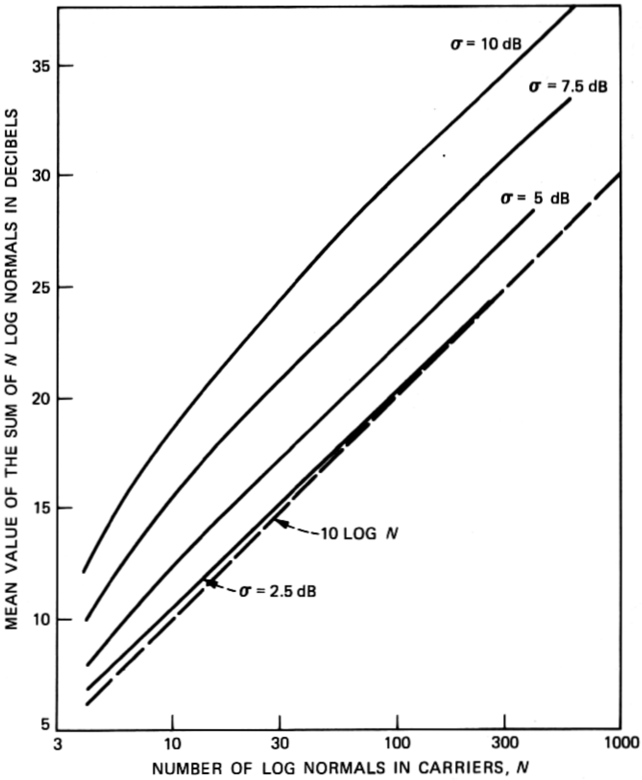


Fig. 5—Mean decibel values of log-normal distribution derived from log normals with same mean and standard deviations.

the time when 100 log-normal carriers are individually transmitted. Figure 6, similar to Fig. 5, is a plot of the mean plus twice the standard deviation of the resultant log normals when a number of identically distributed carriers are summed. Permitting an average power of the value shown in Fig. 6 reduces to 4.3 percent the time fraction that power is not available to meet demand. Compared with the previous example of 100 individually transmitted carriers with $\sigma = 5$ dB, the peak power must now be 24.5 dB above that for a single carrier, about a 2-dB increase.

To ensure 95.7-percent coverage assuming a standard deviation of 5 dB for a single log-normal carrier, requires a margin 10 dB (2σ) above its mean. Thus, it appears that transmitting each carrier with power just sufficient to overcome the path attenuation results in a power savings of about 5.5 dB compared to transmitting all signals with power 10 dB above the mean.

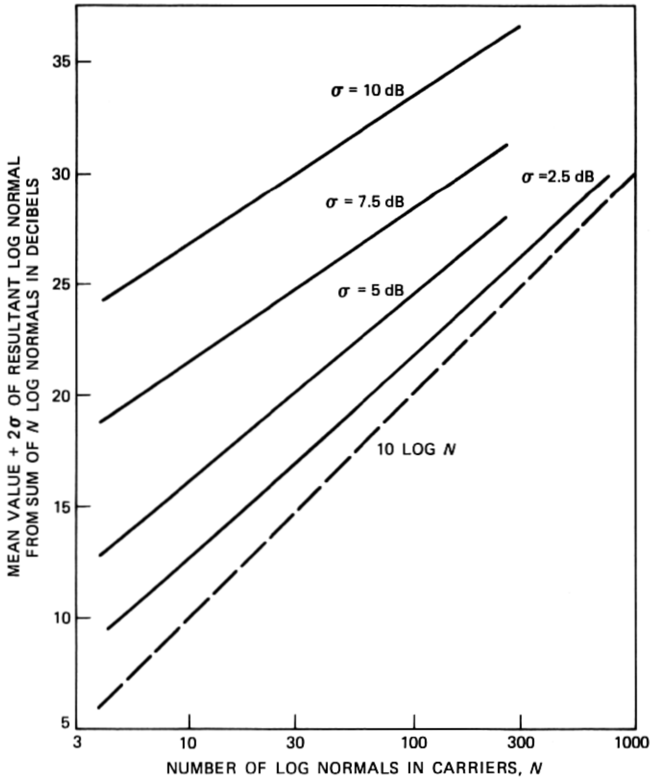


Fig. 6—Plot of mean plus twice the standard deviation of resultant log normals when identically distributed carriers are summed.

5.2 Multicarrier considerations

The calculations above imply that each carrier is transmitted separately. Usually it is far more efficient from the point-of-view of spacecraft hardware and complexity to combine signals and transmit them from a single high-power amplifier rather than employ many (hundreds) of low-power amplifiers. Since the signals add in voltage, the peak power requirement will be considerably above the average; and since amplifiers are not ideal, intermodulation results. Calculations of intermodulation distortion for the case of equal-amplitude but randomly phased signals for both ideal and typical power amplifiers have been made by Saleh.[15] Typical results are shown in Fig. 7. To achieve the minimum acceptable $C/(I + N)$ of 10 dB requires that the average power of an ideal amplifier be "backed off" 3 dB from its peak power and that any realistic amplifier be backed off 3.5 dB from its peak power point. For more typical operating conditions, $C/(I + N) >$ 15 dB, back-offs would be 5 to 7 dB, depending on the amplifier and compensation used. This implies that, even for a power amplifier which is 50 percent efficient at saturation when operated in the linear region, the dc-to-RF efficiency can only be about 12 percent. Still there can be an overall weight savings in the satellite compared to using individual amplifiers, but quantitative calculations are beyond the scope of these considerations.

The power back-off numbers cited are calculated for equal-amplitude carriers with random phases. For the mobile-satellite case with power control, the carriers have independent randomly distributed phases, but the amplitudes are log-normally distributed. Greenstein has reasoned that similar results should be expected for this case; however, the calculations remain to be done.*

5.3 Resource sharing and coding

Resource sharing has been suggested for TDMA systems as a means to increase a link margin by nearly 10 dB. The idea is to assign the user in a shadow fade a longer time slot, and encode the signal. For digital mobile-satellite service, this technique could be considered, but for analog modulation its implementation is less obvious. For resource sharing to be effective, it is necessary that the majority of mobiles not require the use of the additional resource of a coded signal. For a given system bandwidth, the cost of resource sharing is a reduction in

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* Simulations of L. Greenstein and A. Saleh have shown that for sample cases with as few as 100 log-normal carriers with random phases, the resultant envelope tends to be Rayleigh distributed. Thus, at least over time periods where the amplitudes of the carriers, and thus the average power, can be considered fixed, the calculated results based on equal amplitude carriers should be usable.

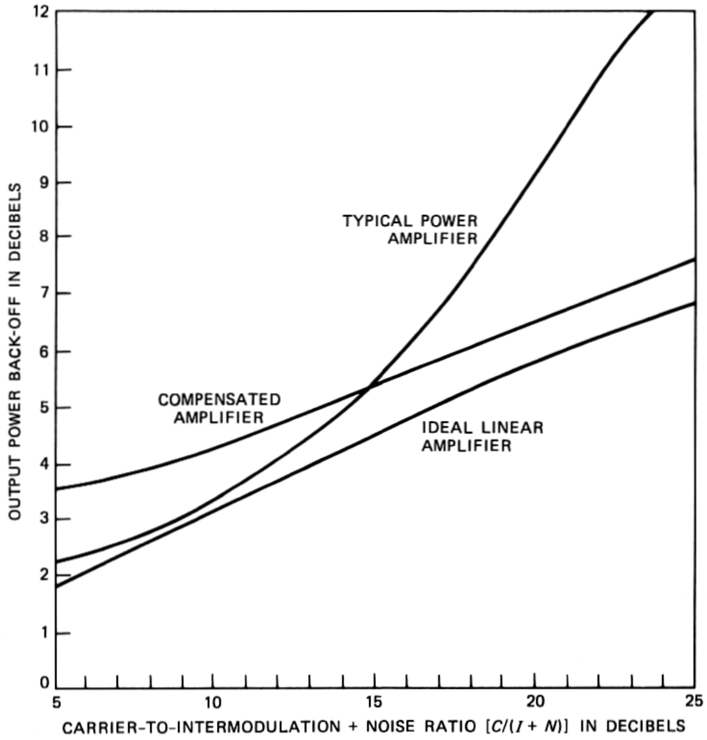

Fig. 7—Back-off required to achieve a given $C/(I + N)$.

transmission rate, but at an increase in margin. For 12/14 GHz fixed-satellite systems, the intent is to apply resource sharing only to those stations experiencing rain fading. Even using a rate 1/3 code (i.e., three transmitted bits per information bit) for these users, it was estimated that the loss in throughput is only a few percent, since very few users need resource sharing simultaneously.[16] As shown in Fig. 8, the throughput drops dramatically when the fraction of simultaneous users of resource sharing becomes significant. The curve in Fig. 8 assumes a fixed total system bandwidth and a rate 1/3 code for users of resource sharing. For example, when 10 percent of the users need resource sharing, the total number of users decreases by 17 percent while, if 50 percent of the users need resource sharing, the system capacity drops to 50 percent of the original value. To ensure that at any one time only a small percentage of the mobiles require resource sharing implies that the system normally operates with a margin somewhat above the median excess path loss. From Fig. 2 we see that (depending upon the degree of optimism), providing somewhere between 6 and 12 dB extra power over free space propagation would

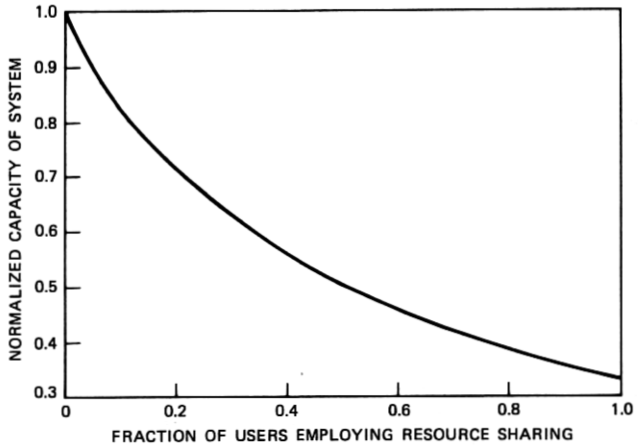

Fig. 8—Capacity loss with resource sharing using rate one-third code.

ensure that fewer than one third of the mobiles would require resource sharing at any given time. The additional margin obtainable from resource sharing then can extend the range of coverage from approximately two thirds of all locations to more than 90 percent. As in the case of power control, resource sharing cannot be applied instantaneously because of the time delays involved from the time measurement to the application of coding. Thus, the application is only for cases of slowly varying changes in signal strength.

The original resource sharing concept assumed that all users shared a single wideband channel. Implementation in a frequency-channelized system is less straightforward. However, if the system is not bandwidth limited, then all channels could use, say, a rate 1/3 code, thereby gaining an advantage of roughly 4 dB, plus or minus a decibel, depending upon the constraint length of the code and the particular implementation of the decoder.[17] Since the channel bandwidth is now three times wider, the mobile receiver is degraded by 5 dB, thus the large apparent gains of resource sharing cannot be realized.

5.4 Trade-offs between radiated power and antenna gain

There are two ways to increase effective radiated power from a satellite. The first is simply to increase the transmitter power. The second is to increase the antenna gain. Although the techniques are equivalent in terms of the radiation to a point on earth, each implementation has different ramifications. Increasing radiated power is relatively straightforward in that the coverage area remains the same, and the burden on the satellite is to obtain more dc power through the use of more solar cells and to provide more battery power for eclipse operation. Note that the eclipses only occur at night when, presumably, usage and power requirements would be greatly reduced.

Normally the satellite-mobile service would not be a broadcast mode, that is, it would not be necessary to talk to more than one mobile system over a single channel; therefore, the information to that mobile system can be confined to a small antenna beam. Thus, having a large number of high-gain beams covering the entire country becomes power efficient, since the power is only radiated in the beam intended for that mobile.[1,2,5] An additional benefit of spot beams is the possibility that the channels can be reused between areas that are spatially separated by a few beamwidths. In the case of conventional point-to-point telephony, demand is spatially nonuniform and highly peaked. If such is the case here, the advantages of reuse cannot be fully realized.

In a recent note it is proved for idealized constraints that maximum EIRP is obtained when the communications payload of the satellite is divided equally between the RF power subsystem and the antenna subsystem.[18] Sample calculations indicate that at frequencies above 1 GHz, multibeam antennas are more effective in increasing EIRP compared to using United States coverage antennas and high-power amplifiers. Earlier it was stated that a satellite providing 53-dBW EIRP (30-dB antenna gain, 200W RF power) could be achieved fairly conveniently. With battery backup either reduced or eliminated, 55 dBW should be attainable in an advanced state-of-the-art satellite using a United States coverage antenna.

Plotted in Fig. 9 are two curves that show EIRP as a function of payload mass. The lower curve is for a satellite with a United States coverage antenna where EIRP is increased only through increased transmitter power. The upper curve is the case where EIRP is maximized by dividing the payload equally between the antenna and the transmitter subsystems. At the point where a satellite with a United States coverage antenna provides 55 dBW, the maximum EIRP available is 58.2 dBW, assuming gain is achieved at 50 times isotropic per kg, and RF power is produced at 2.5 W/kg.* Under these conditions the antenna would weigh 73 kg and have a gain of 35.5 dB, implying three or four zone beam coverage of the United States, and a total RF power of approximately 180W would be transmitted.

Use of spot beams for EIRPs near 55 dB can generate an EIRP increase of about 3 dB. At 900 MHz the antenna diameter is already

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* The units here are somewhat unusual, but for a given frequency, antenna gain is proportional to the antenna surface area that weighs so many kg/m^2. Likewise, power is derived from solar cells producing so many watts/kg. Thus, both antenna gain and RF power can be expressed as functions of mass.

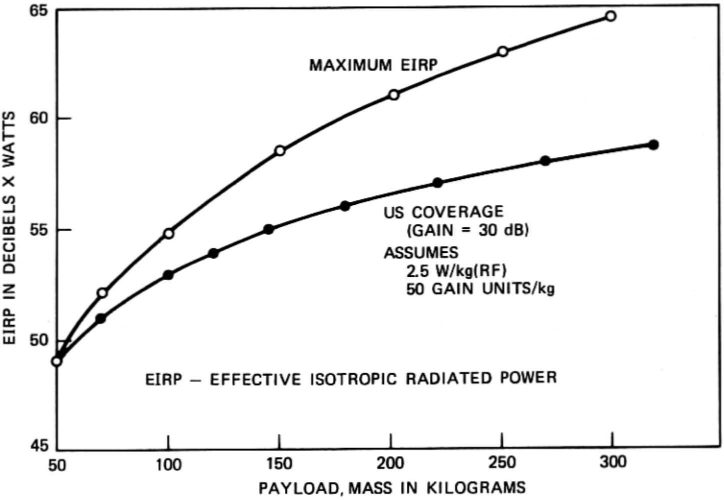

Fig. 9—Effective radiated power as a function of payload mass.

around 8m to provide a gain of 35.5 dB. For large payload satellites with EIRPs of 65 dBW, over 3 kW of RF power would have to be transmitted if United States coverage antennas were used, while use of a spot beam antenna with maximized EIRP permits 65 dBW of radiated power with one quarter the payload mass. Still, the required payload mass is 300 kg, twice the size of most current-day satellites.

5.5 Source coding and narrowband modulation

Although obvious, it should be mentioned that employing narrower band channels improves the predetection CNR. Although modulations such as companded Single-Sideband (SSB) have been demonstrated, their performance in multipath environments will be degraded. Likewise, low-bit-rate voice coders (10 kb/s) may provide reasonable voice quality, but such coders are complex, and whether acceptable performance can be achieved with channel errors is not known. However, since the prospects for compatibility of satellite transmission with present-day land-mobile radio look dismal, the possibility of using other techniques to gain perhaps as much as 6 dB in link budget compared to analog FM need to be investigated further.

5.6 Summary of possible improvements in link budget

Since it is envisioned that much more than a thousand channels are necessary for any practical system, the single-amplifier-per-channel approach is not feasible. The next most straightforward technique is to use multiple carriers on a single (or few) wideband channel. This does not rule out compatibility with FM cellular systems, but major system problems remain.

Multicarrier operation should result in increased payload, and thus higher potential EIRP, but actual increases are difficult to calculate. Back-off can be eliminated if the downlink signals are digital and multiplexed onto a single carrier; however, downlink power control cannot be achieved under this condition. Mobiles would require TDMA receivers, and for bandwidths greater than 1 MHz, reception may be impaired by multipath propagation.

Table IV lists techniques that can potentially increase or decrease effective radiated power. For cellular-like service using a present-day satellite, techniques D, E, F, and G can be applied, yielding possible increases in EIRP from 0 to 8 dB. With SSB an additional 6 dB advantage may be possible (Item C). With digital modulation Item A is added and B replaces C, for a link-budget gain of 3 to 15 dB. With digital multiplexing, D and E are eliminated and H can replace A, for possible link-budget increases of 11 to 19 dB. Finally, using more diversity elements (Item I) helps the link budget significantly, especially at low BER.

VI. CAPACITY CALCULATIONS

Satellite design is very complex, and no claim is made that actual satellites can be designed with the calculated capacities. Rather, the purpose here is to determine the effect in a general sense to some of the many options available. To that end, we make the simplifying assumption that changes in capacity are proportional to changes in effective radiated power. Thus when bandwidth is not a constraining factor, the number of circuits is determined by the simple relationship,

$$C = C_\beta 10^{\left(\frac{G_L - M}{10}\right)},$$

where C_β is the baseline capacity calculated in on a line-of-sight basis

Table IV—Possible improvements in link budget

	Technique	dB Increase
A	Channel coding (Sec. 5.3)	2 to 4
B	Source coding (Sec 5.5)	1 to 3
C	Modulation (receiver bandwidth) (Sec 5.5)	3 to 6
D	Power control on each channel (Sec. 5.1)	3 to 5
E	Back-off loss (Sec. 5.2)	−7 to −4
F	Maximize EIRP (Sec. 5.4)	2 to 4
G	Reduced battery for eclipse (Sec. 5.4)	2 to 3
H	Resource sharing (Sec. 5.3)	6 to 9
I	Diversity elements (3 to 8) (compared to 2) (Sec. 4.0)	5 to 8
J	Double-size payload (Sec. 5.4)	3 to 6
K	Four-times payload (Sec. 5.4)	6 to 12

in Section II, G_L are the gains in the link budget discussed in Section V, and M is the margin determined in Section III for a given grade of service and terrain type.

For example, assume a rather low grade of service with only a 7-dB margin. Combine this with the most optimistic link-budget gain of 19 dB. Then the possible number of circuits is $316 \times 10^{1.2} = 5008$, and a 300-MHz spectrum allocation would be required. More realistically, a 10-dB improvement in the link budget might be obtained for a specially designed satellite system not compatible with current cellular systems. On the other hand a 10-dB margin is almost essential for good service. Taken together the 10-dB improvement is offset by a 10-dB margin and the capacity calculates to the baseline value of about 300 circuits.

VII. DISCUSSION AND CONCLUSIONS

It should be noted that use of diversity and tolerance of more bit errors can lower margin requirements significantly. For example, from Fig. 3 we see that, at 10^{-3} BER, going from two to four diversity elements reduces the margin requirement by 7 dB. Also, using two-branch diversity, but setting the system threshold at 10^{-2} BER instead of 10^{-3} BER, reduces the system margin by over 5 dB. The combination of the four-branch diversity at 10^{-2} BER threshold permits a 9-dB reduction in satellite EIRP compared to two-branch diversity and a 10^{-3} BER threshold. If this power savings could be directly traded for capacity, then eight times the number of circuits could be achieved. Downsizing the baseline calculations for low-bandwidth applications such as paging or emergency telephony is also possible.

As noted in Table IV, there is the potential of economy of scale. Satellite costs tend to run nearly linearly with weight[19], but EIRP can increase with the square of satellite mass;[18] and provided there are no bandwidth constraints, channel capacity can increase in direct proportion to EIRP. Thus, for satellites of twice the size (and at least twice the cost) four times as many circuits are obtained. In-orbit satellite mass as high as 5,000 kg are envisioned using the shuttle/Centaur. This represents a factor of 5 to 10 compared to present-day technology and suggests that future land-mobile service via satellite could become attractive. Trading power for capacity comes at the expense of bandwidth, a very precious commodity. On the other hand, terrestrial cellular systems will reuse frequencies hundreds of times nationwide. Making satellite-mobile systems spectrally efficient through the use of multibeam satellite antennas that can reuse frequencies is a tremendous technical challenge. Mile-diameter antennas are needed to get cell sizes comparable to terrestrial radio systems.

For service to aircraft, a 6-dB antenna gain for an aircraft in level flight seems reasonable, thus, line-of-sight capacity numbers apply directly. For service to residences, an antenna gain of 16 dB is readily obtainable using a 1-m dish. Assuming there is a line-of-sight path and that there is sufficient bandwidth available, about 3000 circuits should be obtainable with present-day satellite capabilities, before power limitations become constraining.

Finally, it is safe to conclude that (1) cellular-compatible satellite-mobile systems are highly unlikely to be developed in the near future, (2) systems with modest-coverage objectives using enhanced-capability satellites and high-performance mobile sets look marginally attractive, and (3) very large satellites offer a possibility for mobile systems, in the long-term.

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