

N89-27913

System Level Comparison of FDMA vs. CDMA (Under Conference Guideline Constraint)

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ABSTRACT

The margin that is required to mitigate the "near-far" problem in a CDMA mobile satellite system is determined by the radio-propagation model selected, the distribution of the users in clear and shadowed environments, and implementation techniques.

The use of revenue potential as a means of evaluating the relative merits of CDMA and FDMA systems is a convenient way to rationalize the performance of systems using high-gain and low-gain antennas. The revenue potential of CDMA is much greater than the revenue potential for FDMA for a particular satellite design considered.

THE NEAR-FAR PROBLEM

The "near-far" problem in CDMA systems occurs where a number of terrestrial mobile unit terminals communicate to a single base station.

Some of the terminals are physically "far" from the base station, some are "far" in a radio propagation sense because they are shadowed, and some are "near" in both a physical and propagation sense.

If the system is using CDMA, the "near" terminals are contributing more self-noise than the "far" terminals. The system design has to somehow allow the "far" terminals to communicate in the presence of the larger self-noise of the "near" terminals. If the system is using FDMA, the carrier levels received at the base station will differ between the "near" and "far" terminals. If the base station can accommodate the dynamic range of the FDMA signals, the "near-far" problem does not limit the system performance.

For the class of satellite system called out in the conference guidelines a CDMA satellite system will be self-noise limited: the downlink signal-to-noise ratio is $E_b/(N_0 + I_0)$, where I_0 is much larger than N_0 . The E_b/I_0 is established at the satellite. A partial shadow does not change the E_b/I_0 ; it only changes the ratio of I_0 to N_0 . On the downlink there is no "near-far" problem.

The "near-far" problem is important on the uplink. The satellite system capacity is limited by the margin allowed for the difference in signal strength of the "near" and "far" terminals.

There is limited fix for the uplink "near-far" problem. The mobile terminal can be equipped with a "short-loop" automatic level control.

The receiver in the vehicle monitors the downlink signal level and uses that information to adjust the uplink signal's level. If the downlink signal fades by 3 dB the uplink transmitter level is increased 3 dB, for example. The uplink E_b/I_0 for the shadowed station should remain constant.

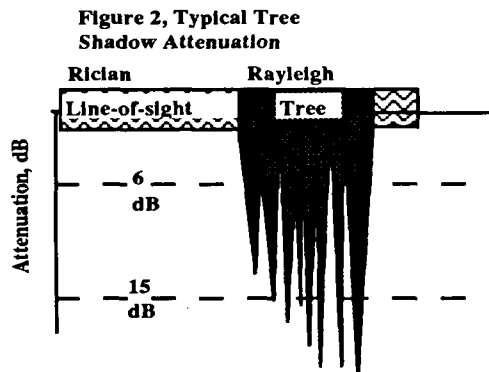
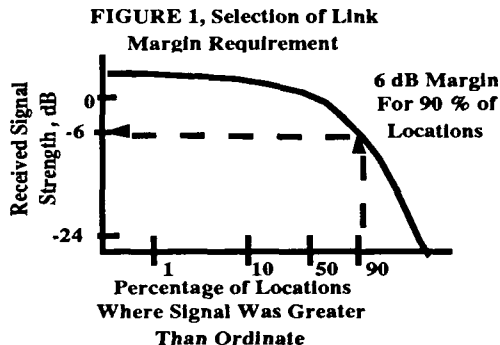
This ALC system could also be used with an FDMA system. However, there is no performance penalty in an FDMA system from operating the transmitter at full power. It is not necessary to control the level.

RADIO PROPAGATION MODEL LIMITATION

The limitation on this near-far fix technique is the practical dynamic range of the mobile transmitter and the correlation between downlink and uplink fading. Field tests were undertaken in order to understand the effectiveness of the "short-loop" automatic level control. The field tests were quite surprising, not because of what was learned about "short-loop" automatic level control,

but because of what was learned about the limitations of the radio propagation model being used.

When the experiment initially was designed the propagation model¹ producing a curve similar to that in figure 1 was being used.



These data would predict that a 6 dB margin would protect against fading and shadowing 90% of the time. What was experienced in a very limited field test program was quite different. If there was a clear, line-of-sight propagation path, very little link margin was required for unimpaired digital voice: about 2 dB margin was sufficient. It was found that almost any tree produced an attenuation of 12-15 dB, far more than considered economically practical for either downlink margins or mobile unit transmitter dynamic range. This conclusion agrees with another line of propagation modeling being pursued in Europe². Figure 2 illustrates the general form of attenuation observed as the vehicle went behind a tree.

A margin of 6 dB was of little value in improving the communications while the vehicle was behind a tree.

As the result of this limited experience, a conclusion was reached which agrees with that in CCIR IWP 8/14³:

"In general the propagation data that is available today is not sufficient to characterize the land mobile case."

It can be concluded that there are two general schools of thought. One fundamentally believes that margins for shadowing are effective. The other believes that margins for shadowing would have to be impracticably large.

SYSTEM IMPLICATIONS OF PROPAGATION MODELS

If the channel capacity for the class of satellite system called out in the conference guidelines is calculated, a CDMA satellite system will be self-noise limited. The CDMA system capacity will generally be determined by the link margin assigned to the vehicle-to-satellite link.

For the same satellite the FDMA capacity will be limited by the link margin assigned to the satellite-to-vehicle link.

In designing a satellite system it is not appropriate to bet the cost of a satellite system (hundreds of millions of dollars) on the universality of whatever propagation model one believes in. It is safer to provide a variety of differently priced services (with different margins) and let the consumer determine the "right" propagation model.

Some users will prefer to use a low-margin service (at a lower per-minute rate) which is restricted to line-of-sight conditions. Users in the unforested Southwestern area of the country or those that operate mainly from clear interstate highways might be happy with a low-cost, low-link-margin service. Users in deeply forested areas might find that they can only communicate from locations where there is line-of-sight. They will be willing to be selective in where they attempt to communicate, rather than pay for a 20 dB margin. Other users will insist on either

having toll-quality speech (not broken up by fading and shadowing) or none at all and will use the low-margin service only in selected locations.

Some users such as emergency vehicles and law enforcement officers will not be able to be selective in where or when they communicate and insist on a service with a large link margin. They may be tolerant of the voice quality varying from "good" to "very poor" as long as they have some communications. Others that live in forested areas with low elevation angles to the satellite may have no choice but to use the high-margin service.

The system engineer must guess at the national market distribution and guess at what the average or aggregate margin will be when they design the system. Since there is no experimental or factual data to support a presumed aggregate margin, it is a matter of personal opinion or conjecture.

The specification of aggregate margin can determine the outcome of the FDMA versus CDMA tradeoff. If a low-aggregate margin is specified, CDMA will have the greatest channel capacity. If a high margin is specified and the FDMA and CDMA systems being compared have a high percentage of the users in each antenna beam, FDMA will have the greatest channel capacity. If the aggregate margin is greater than 4-6 dB FDMA for that class of system described before in reference 4, FDMA will have a greater capacity. Below 4-6 dB link margin CDMA has a greater channel capacity.

In the time since reference 4 was written the CDMA system technology has been improved. The relative efficiency of CDMA and FDMA is not so dependent on margin selection if channelization of the CDMA is used. In the last section of this paper further examples will be shown of channelized CDMA.

REVENUE POTENTIAL AS AN EFFECTIVENESS MEASURE

"Revenue potential" is a more encompassing measure of system effectiveness than simple channel capacity. It can include the cost of the user's vehicle antenna and eliminate the "apples versus oranges" comparison of systems using directional and omnidirectional antennas. Since CDMA systems (under the conference guidelines) are self-noise limited, there is little advantage for them to use directional antennas. FDMA systems are power limited and can gain in capacity by using directional antennas. The total investment of the users in terminal equipment plus the investment in the space segment are different in CDMA and FDMA systems if different vehicle antennas are used. In the following revenue potential calculation the variable is removed by assuming that all users pay the same monthly charge and then calculating the satellite operator's revenue.

For this analysis it is assumed that the average user leases his terminal equipment and uses 150 minutes of airtime per month. Each satellite channel is shared by 60 users. For this example the user cost structure shown in figure 3 will be used.

Figure 3, User Terminal Cost Assumptions

**Radio Costs: Manufacturing, Parts, G/A, Labor +Manufacturer's Profit +
Inventory/Distribution Costs +Sales Cost + Installation Costs + Omni Antenna Cost
+Warranty/Service Cost = \$3,000**

Radio Rental = 5 %/ mo. x \$ 3,000 = \$ 150/mo.

**Antenna Costs: Manufacturing, Parts, Labor +Manufacturer's Profit +
Inventory/Distribution Costs +Sales Cost + Installation Cost - Omni Antenna
Costs +Warranty/Service Cost + Structural Modifications to Vehicle +Repair of
Damage to Vehicle = \$ 2,000**

Antenna Rental: = 5 %/ mo. x \$ 2,000 = \$ 100/ mo.

For brevity only the cost factors and an assumed total cost of each category is shown. It is easy to come up with a set of cost factors to justify those totals. It is assumed that the user pays 5% of the total cost per month as a lease. That is the approximate lease rate for cellular radios.

The revenue model assumes the user is willing to pay the same total amount per month

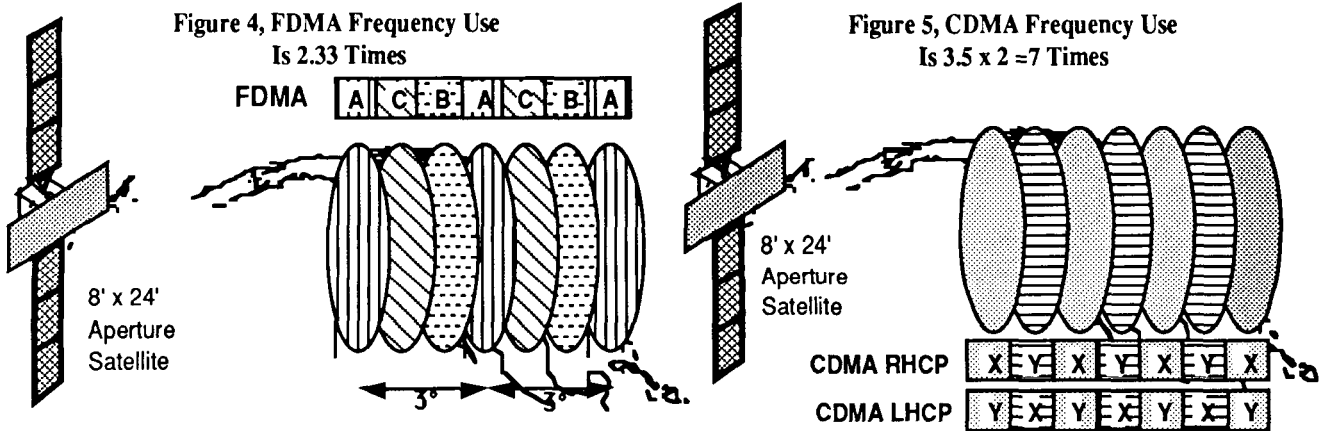
(\$400) whether they have an omnidirectional antenna or a directional antenna.

If the user has a directional antenna, they pay the satellite operator \$150 per month. If they have an omnidirectional antenna, they pay the satellite operator \$250 per month. If there are 60 users per channel, then the satellite operator's revenue potential is either \$9,000 /channel/month or \$15,000 /channel/month, depending on the antenna used.

COMPARISON OF REVENUE POTENTIALS

The satellite that will be assumed is the fan-beam satellite that was described in a previous related paper ⁴. The 7 MHz of bandwidth (allocated by the conference committee, not the FCC or WARC) as shown is assumed. For an FDMA system the band is divided into three 2.33 MHz sub-bands. For the CDMA system the band is channelized into two 3.5 MHz sub-bands.

Figure 4 shows how the frequencies are allocated to antenna beams for an FDMA system. For beams limited to CONUS the frequency-use factor is 2.33.



In an FDMA system the polarization cannot allow an additional frequency use. Multipath reflections from buildings and other objects reverse the sense of the polarization. A signal transmitted on one sense of polarization appears as interference on the opposite polarization after reflection. Since FDMA receivers require 10-dB or more signal-to-noise ratios they cannot tolerate interference that is near the same level.

In figure 5 the CDMA system frequency allocation to beams is shown. CDMA has 3.5 frequency uses and a polarization reuse to give a total use of 7 times.

By alternating the frequency assignment the cochannel interferers are limited to the side of the antenna beam and to the sidelobe regions.

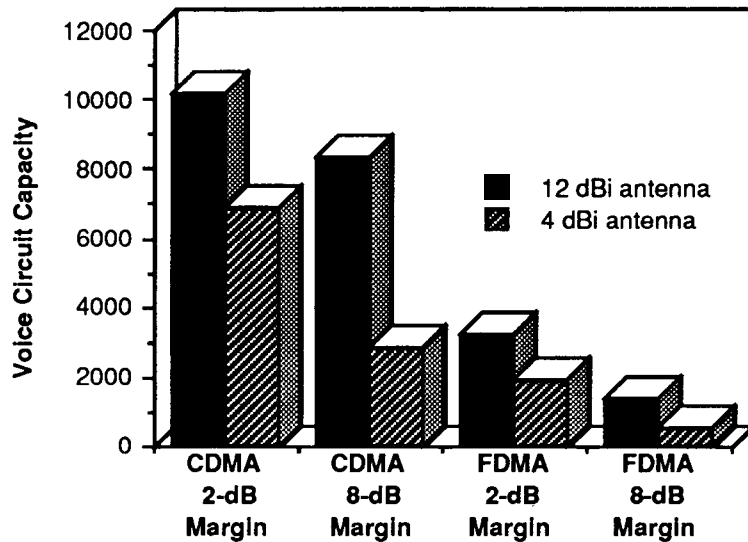
Every other antenna beam uses the same frequency subband. The users in the adjacent beam do not use the same frequency subband and therefore do not contribute to the self-noise of that band. This is in contrast with the system of reference 4 where the cochannel interferers were equally distributed in all beams.

The E_b/N_0 requirements for CDMA and FDMA are quite different. The CDMA requirements are 2.9 dB in the hub-to-mobile direction and 3.9 dB in the mobile-to-hub direction based on actual laboratory tests of rate 1/3 coded BPSK equipment. The satellite-to-mobile link requirement is lower than the mobile-to-satellite link. On the satellite-to-mobile link a single high power reference beacon is used to provide high signal-to-noise timing to all users. On the mobile-to-satellite link the timing must be derived from the data carrier. The FDMA E_b/N_0 requirements are for rate 2/3 TCM/D8PSK are 9.5 dB from reference 5.

The difference in FDMA and CDMA E_b/N_0 requirements is substantial. Because the CDMA requirements are so low polarization reuse of frequencies is possible. The multipath reflected cross-polarized interference levels are much smaller: the signal-to-interference level is much higher than the signal-to-noise required.

The system capacity has been calculated for 2-dB and 8-dB margin requirements and with the use of both directional and omnidirectional antennas. In figure 6 it can be seen that the CDMA channel capacity is substantially greater than the channel capacity of FDMA for both 2-dB and 8-dB aggregate margins.

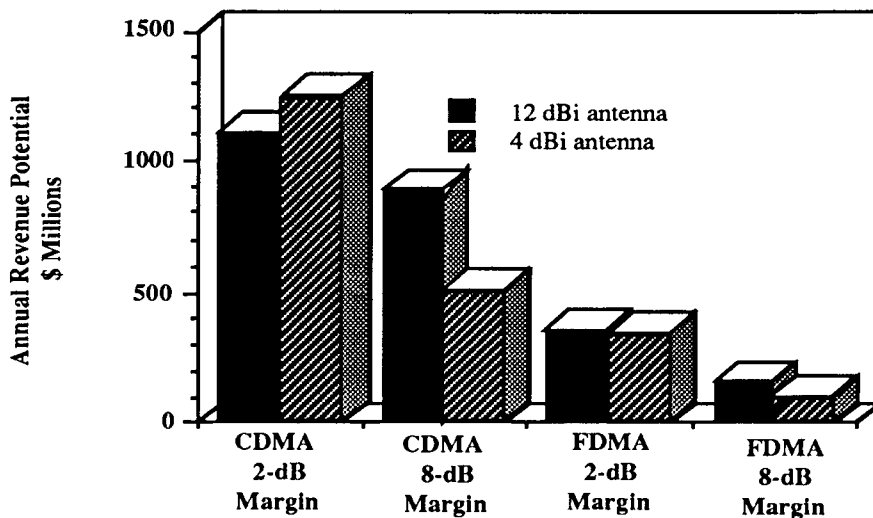
Figure 6, Satellite Channel Capacity



In figure 6 the system capacity does not change in proportion to the antenna gain changes. For the FDMA high-margin cases a substantial amount of power is used in the K-band backhaul to provide the margin on that link. That is why 8 dB change of antenna gain only increases the capacity by approximately a factor of three. The FDMA low-margin case with the high-gain antenna is bandwidth-limited to 3200 channels: the difference in capacity between the low-gain and high-gain cases is not as large as expected because of the bandwidth limit. In the CDMA low-margin cases the system is self-noise limited and the additional gain of the antenna does not make much difference. In the CDMA high-margin examples the 4-dB antenna causes the system to operate in a power limited mode. The 12-dB antenna causes the system to approach self-noise limitation: the capacity does not increase proportional to the antenna-gain difference.

It should also be noted in figure 6 that a single CDMA satellite will allow the capacity of approximately three comparable FDMA satellites.

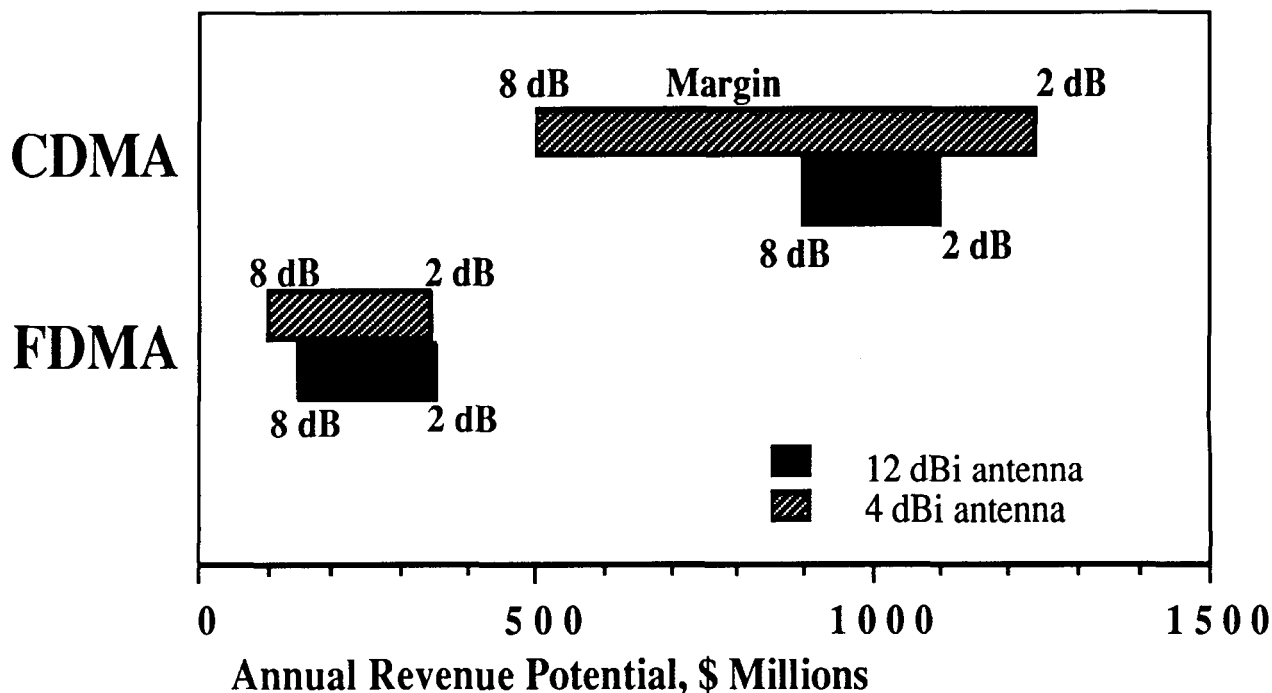
Figure 7, Revenue Potential



If the channel capacities are multiplied by the revenue potential for each class of link, as outlined above, the results shown in figure 7 are developed. Using the revenue potential criteria tends to even

out the differences between the high-gain and low-gain cases. It can be seen that CDMA has a much greater revenue potential than FDMA. The presentation of the same data in the form of figure 8 can bring some interesting additional insight. Previously it was mentioned that there is room for disagreement about the propagation model and the aggregate margin required. The consumers' preference for directional or omnidirectional antennas is also not well understood. We can also speculate on the consumers' willingness to pay for margin. Figure 8 provides the range of annual revenue potential as a function of margin and antenna preference.

Figure 8, Range of CDMA and FDMA Revenue Potential Versus Link Margin



It is clear from figure 8 that even with the uncertainties of margin requirements CDMA will offer hundreds of millions of dollars per year greater revenue potential. The system operator has the potential of making more money offering a CDMA service with 8-dB aggregate link margin than they would offering a FDMA service with 2-dB margin. The system operator also has the potential of making more money with one CDMA satellite than three comparable FDMA satellites.

References

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