N88-25724

COMPARISON OF CDMA AND FDMA FOR THE MOBILESTAR^{sm} SYSTEM

I.M. Jacobs, K.S.Gilhousen, L.A.Weaver, Qualcomm Inc, United States;
K. Renshaw,T. Murphy, Hughes Aircraft Company, United States.

Hughes Aircraft Company
Space and Communicatons Group
Po.Box 92919, S65/J317
Los angeles CA 90009

ABSTRACT

Spread spectrum CDMA and single channel per carrier FDMA systems are compared for spectral efficiency. CDMA is shown to have greater maximum throughput than FDMA for the MobileStar^{sm} system which uses digital voice activated carriers and directive circularly polarized satellite antennas.

INTRODUCTION

Spread spectrum CDMA systems and single channel per carrier FDMA systems have been compared in the literature many times. When bandwidth efficiency is used as the criteria the comparison usually favors FDMA . Viterbi (1) performed such a comparison using five different rate convolutional codes. This paper extends the comparison for the MobileStar^{sm} system.

If FDMA is used in the MobileStar^{sm} system, the system will be designed to be bandwidth limited. In either the first or second generation of satellites, the satellite transponder bandwidth will be filled with users before all of the satellite transponder power is used. In representative system designs under consideration QPSK modulation with rate 7/8 coding is used in order to conserve bandwidth while allowing a coding gain of approximately 3.2 dB.

If CDMA is used in the MobileStar^{sm} system, a low rate can be used. Viterbi (2) has shown that coding does not reduce the effective processing gain in a spread spectrum system. A rate 1/3 code can be used to provide a 6.2 dB coding gain without reducing the system capacity.

PREVIOUS COMPARISONS

In reference (1) the spectral efficiency for BPSK CDMA and FDMA is shown to be given by:

$$\eta = \frac{\frac{C}{N_O W_S}}{\frac{E_b}{N_O'}\left(1+\frac{C}{N_O W_S}\left(\frac{M-1}{M}\right)\right)} \approx \frac{\frac{C}{N_O W_S}}{\frac{E_b}{N_O'}\left(1+\frac{C}{N_O W_S}\right)} \qquad [1]$$

Where:

- C = Total carrier power.
- W_S = Total bandwidth=CDMA chip rate
- E_b/N_O' = Bit Energy/Noise spectral density required for given error rate.
- N_O = Thermal noise power spectral density.
- M = number of users in the system.

For FDMA, there is only one user per bandwidth segment, therefore for M=1 equation 1 becomes:

$$\eta = \frac{\frac{C}{N_o W_s}}{E_b/N_o'} \qquad \text{for } \frac{MR_b}{W_s} < r\log_2(m)$$

And due to the bandwidth limit:

$$\eta = r\log_2(m) = \text{Max } \eta_{FDMA} \qquad \text{for } \frac{MR_b}{W_s} \geq r\log_2(m) \qquad [2]$$

Where:

- r = Number of information bits per baud.
- m = Signal dimension (BPSK: m=2; QPSK: m=4 etc.).
- R_b = Users information bit rate.

To relate this previous work to the MobileStar[sm] system, the two modulation types thought to be appropriate: FDMA QPSK with a rate 7/8 code and CDMA with a rate 1/3 code; are compared below.

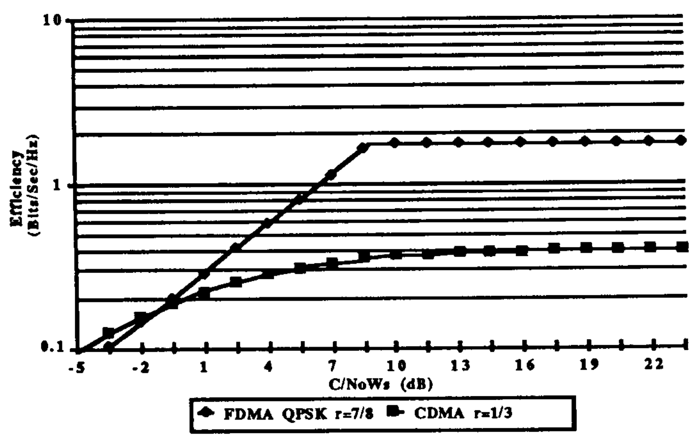

Figure 1. Comparison of efficiency (throughput in bits/sec/Hz) for FDMA QPSK rate 7/8 coded and CDMA rate 1/3.

The result shown in figure 1 is typical of that found in system studies such as (3). It was found that at large signal to noise ratios FDMA (QPSK rate 7/8) has 4.4 times greater capacity than CDMA (rate 1/3). As the signal to noise ratio gets very large the CDMA system capacity is limited by the co-channel noise or self noise. This self noise limitation can be calculated by taking the limit of equation [1] as the carrier power approaches infinity.

$$\text{Max } \eta_{CDMA} = \lim_{C\to\infty} \frac{\frac{C}{N_o W_s}}{\frac{E_b}{N_o'}\left(1+\frac{C}{N_o W_s}\right)} = \frac{1}{\frac{E_b}{N_o'}} \qquad [3]$$

The maximum efficiencies for the two modulation types can be compared using equations 1 and 2 (with m=2 and E_b/N_o'=4 dB[1]).

$$\frac{\text{Max } \eta_{FDMA}}{\text{Max } \eta_{CDMA}} = \frac{[r \log_2(m)]_{FDMA}}{\left[\frac{1}{E_b/N_o'}\right]_{CDMA}} = \frac{\frac{7}{8}\,2}{\frac{1}{2.51}} = 4.39 \qquad [4]$$

COMPARISON INCLUDING SYSTEM CONSIDERATIONS

Several factors have been identified that can alter the comparison between FDMA and CDMA. In a conference paper by Viterbi (4) and also in a system study (5) undertaken to evaluate the application of CDMA to mobile satellite communications it was found that the mobile environment has two additional factors that may reduce the self noise density and greatly alter the result of the comparison. These factors are voice activity and spatial discrimination provided by satellite steerable array antennas and multiple satellites. Similarly, antenna polarization may be exploited in order to effectively reuse the available spectrum in a CDMA system. In general, any factor which can reduce the self noise experienced by an individual channel will favorably effect the relative efficiency of CDMA.

Voice activity will greatly reduce the self noise of a CDMA system. MobileStar[sm] market projections indicate that 95% of the satellite channels will be used by voice services. The voice services will use voice activated carrier transmitters such that when a user is listening or has paused in the conversation, the transmitter's spread spectrum carrier is turned off and the user does not contribute self noise to the system. Conventional telephone practice (6) for satellite circuits indicates that a given user will only be talking approximately 35% of the time.

If the FDMA system is bandwidth limited, the voice activity factor does not increase capacity. A pair of circuits is allocated to a conversation for the duration of the call. When a user is listening, the circuit is still assigned to the user. The voice activity factor reduces the necessary satellite transmitter power by the activity factor and therefore increases the capacity when the satellite is operating in the power limited mode. This has the effect of shifting the FDMA line in figure 1 to the left by the voice activity factor. However, the voice activity factor does not increase the maximum number of circuits that can be assigned when the system is bandwidth limited.

Satellite antenna discrimination may be used to further reduce the system self noise observed by a particular channel. For example, a satellite with an 8 ft. x 24 ft. antenna aperture may be used to produce the type of coverage shown in figure 2. For this analysis it will be assumed that an optimal beam is formed centered on the user's longitude. If a user is transmitting a signal from a location corresponding to the center of a beam, as shown in figure 3, the satellite receives its signal at full strength, and pseudo-noise from all of the other users, such as those in other beams, are received at reduced strength. Since the pseudo-noise powers are weighted by the antenna gain, only the interferers close to the beam center contribute a large amount of co-channel noise. A sample calculation has been performed using simulated antenna patterns for the 8 ft. x 24 ft. antenna aperture. Assuming a uniform user distribution within the United States, the beam with the worst case coverage will collect only 21% of the energy of the transmitted by the entire user population. This implies that the antenna will discriminate against all but 21% of the total system self noise.

The FDMA system will also gain from the use of the above antenna. The antenna coverage can be designed to allow frequency reuse every 3°. The frequencies used in beam 1 can be reused in beam 4 and beam 7. The intersection of the coverage shown in figure 2 with and assumed uniformly distributed user population in the continental United States indicates that the full spectrum can be used twice. Hence, for FDMA the bandwidth limitation is doubled.

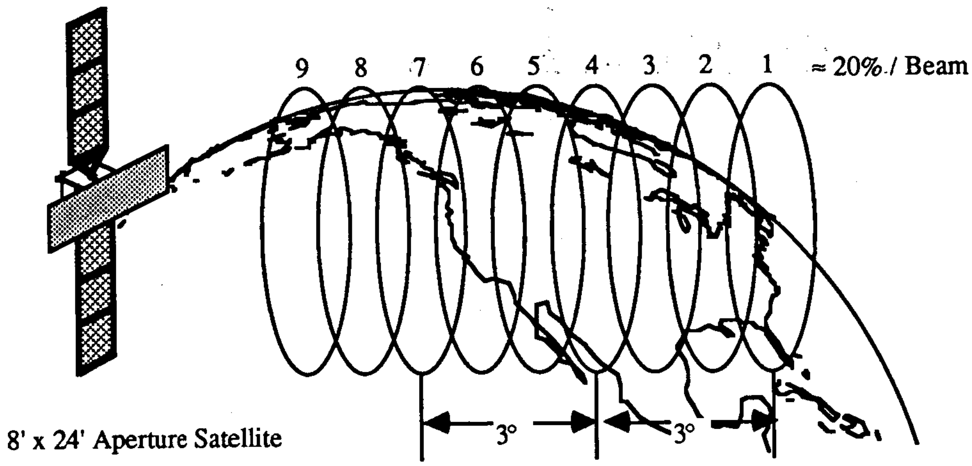

Figure 2. Assumed Antenna Coverage.

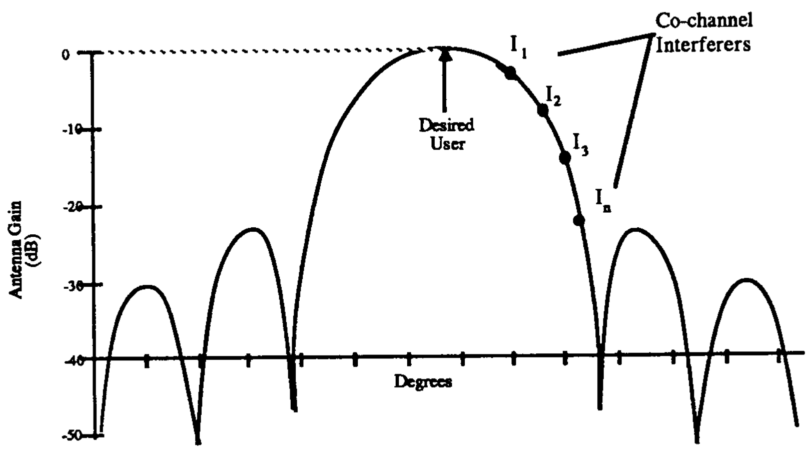

Figure 3. Co-channel (self noise) interference sources are attenuated by the antenna pattern.

In the case of CDMA the available frequency band can effectively be reused by utilizing the two opposite senses of circular polarization. The self noise is divided between the polarizations. This reuse is possible because the self noise affecting a particular channel is the sum of the self noise of the users with the same polarization plus the self noise from the users with the other polarization *attenuated by the crosspolarization ratio.* Also the self noise of the multipath-reflected signals of users operating on the opposite polarization must be considered. If a given CDMA mobile unit is operating beside a large reflective building or a truck in the next highway lane, its reflected energy will increase the interference on the opposite polarization by a factor of 1/M. For the purpose of this comparison we shall assume that the *average* ratio of the desired polarization to the cross-polarization is 10 dB.

In an FDMA system the polarization isolation cannot be used to reuse frequencies at a given orbital slot. Reflected signals will appear at the full reflected power in the channel of the mobile unit operating on the opposite polarization sense. Under these conditions, mobile units would find themselves being jammed intermittently by users on the opposite sense polarization.

To compare FDMA and CDMA from the viewpoint of the MobileStar^{sm} system we define the orbit slot spectral efficiency to be the *maximum throughput* (nominal data rate times the number of users) of the system as a function of the *average carrier to noise power ratio.* We use this definition because the revenue of the system is directly related to the maximum throughput of the system. Also the cost of the satellite system is influenced by the power required. Therefore, in designing the satellite system we are interested in the average required carrier power.

An expression for the orbit slot spectral efficiency (in bits/sec/Hz) which include the effects of voice activation, antenna discrimination and polarization reuse can easily be derived. First the total noise seen by a given user can be expressed:

$$N_o' = N_o + a\rho V(M-1)E_s \qquad [5]$$

Where:

a = Antenna discrimination factor.

ρ = Polarization reuse factor calculated by:

$$\rho = \frac{(1+\text{ Cross Polarization Level})}{2}$$

V = Voice activity factor

E_s = Received energy in one pseudonoise chip.

so then,

$$\frac{E_b}{N_o'} = \frac{\frac{E_b}{N_o}}{1 + a\rho V(M-1)\frac{R_b}{W_s}\frac{E_b}{N_o}} \qquad [6]$$

System performance is to be measured by the orbit slot efficiency (or throughput) - MR_b/W_s, as a function of the *average* C/N_oW_s. The average C/N_oW_s is given by:

$$\frac{C}{N_oW_s} = VM\frac{R_b}{W_s}\frac{E_b}{N_o} \qquad [7]$$

From equations 6 and 7 it can be shown that the orbit slot spectral efficiency is given by:

$$\eta_{slot} = \frac{MR_b}{W_s} = \frac{\frac{C}{N_oW_s}}{V\frac{E_b}{N_o}} = \frac{\frac{C}{N_oW_s}}{V\frac{E_b}{N_o'}\left(1+a\rho\frac{C}{N_oW_s}\left(\frac{M-1}{M}\right)\right)} \approx \frac{\frac{C}{N_oW_s}}{V\frac{E_b}{N_o'}\left(1+a\rho\frac{C}{N_oW_s}\right)} \qquad [8]$$

The new self noise limitation can be calculated by taking the limit as before.

$$\text{Max } \eta_{CDMA} = \lim_{C\to\infty} \frac{\frac{C}{N_oW_s}}{V\frac{E_b}{N_o'}\left(1+a\rho\frac{C}{N_oW_s}\right)} = \frac{1}{Va\rho\frac{E_b}{N_o'}} \qquad [9]$$

The orbit slot spectral efficiencies for the FDMA QPSK rate 7/8 coded and CDMA rate 1/3 coded cases can be compared using a=21%, ρ=0.55 (10 dB crosspolarization) V=35%, and E_b/N_o' = 4 dB for CDMA.

$$\frac{\text{Max } \eta_{FDMA}}{\text{Max } \eta_{CDMA}} = \frac{\left[r\text{ (freq reuses) }\log_2(m)\right]_{FDMA}}{\left[\frac{1}{Va\rho(E_b/N_o')}\right]_{CDMA}} = \frac{\frac{7}{8}(2)2}{\frac{1}{0.35(0.21)(0.55)2.51}} = 0.36 \qquad [10]$$

From equation 10 it can be seen that for the assumed system parameters CDMA has 2.82 times greater maximum throughput than FDMA.

Equation 8 is plotted in figure 4. Relative to figure 1, the FDMA diagonal line is shifted to the left by the voice activity factor and the bandwidth limitation ceiling is shifted up by; 1) using QPSK and 2)the frequency reuse attributable to the satellite antenna spatial isolation illustrated in figure 2.

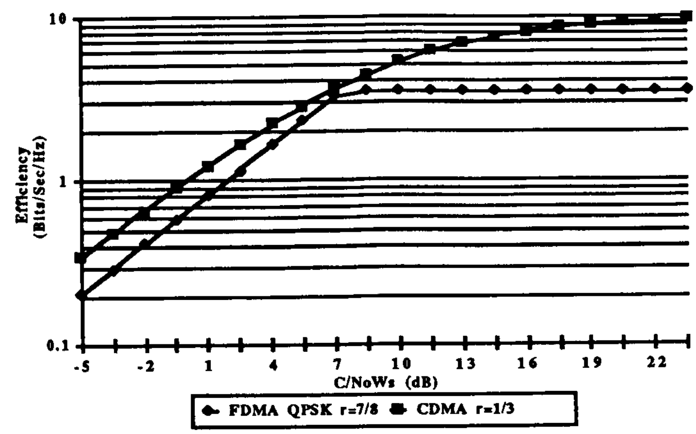

Figure 4. Comparison of orbit slot spectral efficiency (throughput) for FDMA QPSK rate 7/8 coded and CDMA rate 1/3. The effects of antenna discrimination, voice activity factor, and polarization reuse are included.

The CDMA curve is recalculated according to equation 9. It is seen that for these system specific parameters CDMA has greater orbit slot spectral efficiency than FDMA. In a MobileStar^{sm} system context, for a given satellite power, C, and a given frequency allocation, W_s, and nominal user bit rate, R_b, the number of simultaneous users, M, is higher when using CDMA than when using FDMA.

When the demand for service grows beyond that which can be provided by a single satellite, then additional satellites must be provided. However, most mobile terminals will be equipped with very simple omni-directional antennas. Use of CDMA will allow coherent combining of signals transmitted between a terminal and both (or all) satellites in view. This coherent combining will result in an effective system capacity gain corresponding to the increased number of satellites. FDMA, on the other hand, can not provide increased capacity with additional satellites unless each mobile terminal is provided with a costly directive antenna.

References:

1 A.J. Viterbi, "When Not to Spread Spectrum- A Sequel", IEEE Communications Magazine, Vol. 23,No 4, (April 1985), pp.12-17

2 A.J. Viterbi, "Spread Spectrum Communications- Myths and Realities", IEEE Communications Society Magazine, Vol.17,No 3, (May 1979), pp.11-18

3 B.A. Mazur, M Mohler, "Aeronautical Mobile Satellite System Considerations: Detailed Comparison of FDMA Versus CDMA" Miller Communications Systems Ltd. report,(August 29,1986). Presented to ICAO Special Committee on Future Air Navigation Systems Working Group, Washington D.C., September 1986.

4 A.J. Viterbi, Presentation at IEEE Communication Society Workshop on Communication Theory, Palm Springs. CA. April 28, 1986.

5 L. Weaver, "Final Report for Hughes Communications on System Studies for a CDMA Mobile Satellite System", (Oct 28,1986), Qualcomm,Inc.

6 J.M Fraser, "Engineering Aspects of TASI",The Bell System Technical Journal, Vol. 38, No 2, (Mar 1959), pp.353-365