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Diversity Reception for Advanced Multi-Satellite Networks : a CDMA Approach

E. Colzi*, R. De Gaudenzi *, C. Elia*, F. Giannetti **, R. Viola*

* European Space Agency
European Space Research and Technology Centre, RF System Division
P.O. Box 299, 2200 AG Noordwijk, The Netherlands

** University of Pisa
Dipartimento di Ingegneria della Informazione
Via Diotisalvi 2, 56126 Pisa, Italy

Abstract

Diversity reception for Synchronous CDMA (S-CDMA) is introduced and analyzed. A Gaussian co-channel synchronous and asynchronous interference approximation is derived to evaluate the effects on the system bit error rate. Numerical results are provided for a simple mobile communication system where the signals transmitted by two distinct satellite in visibility are coherently combined by a three fingers Rake receiver. A second example showing performance of an integrated ground / satellite single frequency network for digital audio broadcasting is presented. Results show the capacity advantage of utilizing S-CDMA in combination with diversity reception.

1 Introduction

In this paper we will analyze the viability of synchronized code division multiple access, in presence of multipath and fading channel. The presence of a number of signal replicas resolvable in time at the receiver side will be in general called 'multipath' with the understanding that this might be the result of either an intentional satellite diversity or caused by signal reflections.

In case of satellite and terrestrial communication systems utilizing portable receivers equipped with omnidirectional antenna, efficient techniques shall be employed to counteract the performance degradation due to the frequency selective nature of the channel. Multipath processing offers an significant improvement together with the following system advantages:

- *Diversity combining and satellite soft hand-over.* In case of multi-satellite networks, satellite diversity (Fig. 1) can be exploited, allowing to increase service availability and to reduce propagation margins.
- *Multipath combining.* Multipath propagation can create additional diversity condition. In some cases the local signal reflections can advantageously be used for improving the system performance.

To simplify the analysis, we consider in the following, the case of signals originated in the same physical location. This approximates well the case of satellite-to-mobile links and all broadcasting applications.

2 Multipath Effects: System Performance Evaluation

In ref. [1] it has been introduced a S-CDMA system that, while retaining distinctive advantages of CDMA, offers efficient utilization of power and bandwidth.

In fact, by using orthogonal code sets, the inter-user interference is drastically reduced. This implies that the system capacity is not limited by self-noise. Moreover S-CDMA can contain an embedded reference code ("master code") that simplifies the chip timing and carrier phase extraction at the receiver side, permitting coherent signal detection in mobile conditions. In summary, the main system features considered for further analysis are:

- A set of M independent data sources code division multiplexed. Preferentially phased Gold codes are utilized as spreading sequences The *master code* constitutes the reference for receiver synchronization and channel sounding.
- The communication channels are direct-sequence QPSK modulated (DS-QPSK). In general the I and Q spreading sequences are different. Transmitted signal bandwidth limitation is obtained by means of square-root raised-cosine Nyquist chip shaping.

The channel considered is a time-varying multipath channel with an impulse response referred to the nominal carrier angular frequency ω_0 of the type:

$$h_c(\tau;t) \;=\; \sum_{i=1}^{L} \beta_i(t)\delta(\tau-\tau_i)\exp j\left[\Delta\omega_i(\tau-\tau_i) \,+\, \theta_i(t)\right]$$

where L is the total number of paths and $\beta_i(t)$, $\Delta\omega_i(t)$, $\theta_i(t)$, $\tau_i(t)$ are the i-th path amplitude, frequency shift, phase and delay respectively. In general they can be modeled as stationary ergodic processes. We assume that the bandwidth of each process is much lower than the symbol rate in order to consider constant all the channel parameters in one symbol. The time dependence of these parameters will not be further reported in our notation for simplicity. To ease analytical derivations we also assume that $\tau_i = (i-1)T_C$, where T_C is the signature code chip duration time. Therefore, only delays of multiple integer of the chip duration time are considered. By simulation it has been verified that the results are very much the same for the case of non integer chip delays.

In the following, we derive an approximate expression of the bit error rate (BER) for S-CDM systems in time-varying multipath channels.

Let us introduce the following notation

M	number of active DS-QPSK users
P	user signal power
$d^l_{p,k}$	k-th data bit; in-phase $l-$th user
$d^l_{q,k}$	k-th data bit; in-quadr. $l-$th user
$\underline{c}^l_p$	I signature seq. vector, $l-$th user
$\underline{c}^l_q$	Q signature seq. vector, $l-$th user
T_S	symbol duration time
$T_b = T_S/2$	bit duration time
$G_p = N/2$	processing gain
$n(t)$	AWGN one sided spect. density N_0
$\vert\cdot\vert_N \triangleq \cdot \; mod \; N$	
$\{\cdot\}_N \triangleq int\left\{\frac{\cdot}{N}\right\}$	

We also define

$$\underline{\underline{S}}_z \;\triangleq\; [\underline{c}^1_z \; \underline{c}^2_z \; . \; . \; . \; \underline{c}^M_z] \qquad z = p, q \qquad (1)$$

$$[\underline{x}_{z,k}]^T \;\triangleq\; [d^1_{z,k} \; d^2_{z,k} \; . \; . \; . \; d^M_{z,k}] \qquad z = p, q \quad (2)$$

and the $(N \times N)$ shift matrices $\underline{\underline{U}}$ and $\underline{\underline{D}}$ such that: $U_{ij} = \delta_{i,j-1}$ and $\underline{\underline{D}} \triangleq \underline{\underline{U}}^T$, where δ is the Kronecker delta.

To calculate the degradation introduced by multipath propagation, we assume coherent detection of the line of sight (LOS) signal. In other words, the receiver is synchronized in frequency, phase, and timing to the LOS signal, ignoring the presence of multipath. Fig. 2 illustrates the reference demodulator. We can collect the N samples per symbol at the output of the chip matched filter into a vector $\underline{y}$ of length N.

$$\begin{aligned}\underline{y}_k &= \underline{y}_{p,k} + j\underline{y}_{q,k} \;=\; \sqrt{P}\Big\{\underline{\underline{S}}_p\underline{x}_{p,k} + j\underline{\underline{S}}_q\underline{x}_{q,k} \\ &+ \textstyle\sum_{i=1}^{L} \beta_i \exp(j\phi_i)\Big[\underline{\underline{D}}^{|i|_N}\left(\underline{\underline{S}}_p\underline{x}_{p,k-\{i\}_N} + j\underline{\underline{S}}_q\underline{x}_{q,k-\{i\}_N}\right) \\ &+ \underline{\underline{U}}^{N-|i|_N}\left(\underline{\underline{S}}_p\underline{x}_{p,k-1-\{i\}_N} + j\underline{\underline{S}}_q\underline{x}_{q,k-1-\{i\}_N}\right)\Big]\Big\} + \underline{n}_k\end{aligned}$$

In the above formula we have neglected the effect of interchip interference. This is justified by the fact that we use raised-cosine chip shaping and we have assumed perfectly synchronized spreading sequences at chip level. $\underline{n}_k$ is the vector of complex AWGN samples at the chip matched filter output. ϕ_i includes the channel phase rotation due to a frequency shift ($\phi_i = \Delta\omega_i t + \theta_i$). The use of $|\cdot|_N \triangleq \cdot \; mod \; N$ and $\{\cdot\}_N \triangleq int\left\{\frac{\cdot}{N}\right\}$ allows to take into account delays larger than $T_S = NT_C$

Since many independent users contribute to the total self-noise interference, the condition for the application of the central limit theorem is fulfilled. Therefore we can assume the interference as a Gaussian process.

Furthermore, assuming ϕ_i uniformly distributed in $[0, 2\pi)$, we can easily evaluate an approximate bit error probability through the use of the equivalent signal-to-noise ratio.

$$P^{l,p}_e(\underline{\beta}) \simeq Q\left(\sqrt{\frac{\frac{2E_b}{N_0}\beta_1^2}{\left\{1 + \beta_1^2\frac{M-1}{2G_p^2}\frac{E_b}{N_0} + \left\{\sum_{j=2}^{L}\beta_j^2\right\}\frac{M}{G_p}\frac{E_b}{N_0}\right\}}}\right) \qquad (3)$$

where $\underline{\beta} = (\beta_1, \beta_2, \; ..... \; \beta_L)$. In the above formula we recognize at denominator the contribution of synchronous and asynchronous interference to the overall signal-to-noise ratio. The probability of error , once the system parameters are fixed, is only function of the vector of path amplitudes $\underline{\beta}$.

In some cases it is interesting to evaluate the average bit error probability

$$P^{l,p}_e = \int_0^{+\infty} \cdot\cdot \int_0^{+\infty} P^{l,p}_e(\beta_1, \beta_2, \cdot\cdot, \beta_L)\, p(\beta_1) \cdot\cdot p(\beta_L)\, d\beta_1 \cdots d\beta_L \qquad (4)$$

We can find a similar expression for the in-quadrature branch. The total probability of error will be

$$P^l_e \;=\; \frac{1}{2}\left(P^{l,p}_e + P^{l,q}_e\right) \qquad (5)$$

Eqns. 3 and 4 have been successfully validated through extensive time-domain system computer simulation. Fig. 3 gives the results for different value of carrier-to-multipath ratio.

3 Study Case 1: Rake Receiver for Multi-satellite Reception

In this section we will examine the performance of a coherent Rake receiver [2]. Some quantitative results obtained from the theoretical analysis derived in the previous section are compared with time-domain simulation results. We consider a system using Gold codes with a code length N=63, 15 direct sequence QPSK users utilizing different I and Q codes.

To validate the analytical results we assume two channel models:

a) *The static channel*, in which some of the channel parameters, namely L, β_j , are fixed. This channel well approximates the case of very slowly variant channels. The static channel is representative of receiving two satellite in LOS visibility, neither with shadowing nor multipath, the two satellite having different received power levels (different relative C/M) due to different terminal antenna gain in each satellite direction and/or different slant range.

b) *The time-varying channel*, each satellite channel is modeled as a lognormal LOS signal plus a delayed multipath component with the same lognormal distribution. The fading processes representing the two satellite contributions are assumed to be independent. The lognormal LOS shadowing process standard deviation is set to a relatively high value (5 dB) to represent the case of a low elevation satellite link. The C/M for each satellite is set to 10 dB.

The assumptions for the channel model are summarized in Table 1. Fig. 4 shows the architecture of a K-path coherent Rake receiver. The K strongest received paths are individually demodulated by K independent receiver branches. The demodulator outputs are then weighted and coherently combined.

The weight determination is eased by assuming that all paths are statistically independent. The optimal weights are determined by maximizing the equivalent signal-to-noise ratio at the output of the combiner $\left(\left(\frac{E_b}{N_0}\right)^{out}_{eq}\right)$. It can be shown that for a K-path Rake receiver

$$\left(\frac{E_b}{N_{tot}}\right)^{out}_{eq} = \frac{E_b\gamma_S}{N_0\gamma_0 + I_S\gamma_S + I_A\gamma_A} \tag{6}$$

where W_i is i-th branch weight,

$$I_A = \frac{M}{G_p}E_b \qquad I_S = \frac{M-1}{2G_p^2}E_b \tag{7}$$

and

$$\gamma_0 = \sum_{m=1}^{K} W_m^2; \gamma_S = \left[\sum_{m=1}^{K} \beta_m W_m\right]^2; \gamma_A = \left[\sum_{j=1}^{K} W_j^2 \left(\sum_{m=1;m\neq j}^{K} \beta_m^2\right)\right] \tag{8}$$

The weight values that maximize $\left(\left(\frac{E_b}{N_0}\right)^{out}_{eq}\right)$ result to be

$$W_i = \frac{\beta_i(N_0 + I_A\sum_{j=2}^{K}\beta_j^2)}{\beta_1(N_0 + I_A\sum_{j=1,j\neq i}^{L}\beta_j^2)} \tag{9}$$

When estimation of N_o is difficult to perform , a sub-optimal solution is to set $W_i = \beta_i/\beta_1$. Fig. 5 shows the Rake receiver performance for the static channel. We notice, in this case, a performance improvement due to combining at low C/M (cfr. Fig. 3). In case of high C/M, the presence of a strong path produces such an increase of asynchronous interference on the other Rake branches to render almost useless the combining process.

A more noticeable gain is produced by the Rake when the time-varying channel is considered. Fig. 6 compares Rake and conventional receiver BER using the conditions defined in table 1. In these cases the Rake receiver in presence of a signal coming from two different satellite having independent fade distribution, provides a considerable gain due to its inherent diversity capability.

Channel	Sat-1		Sat-2	
	μ (dB)	σ (dB)	μ (dB)	σ (dB)
Static	0	0	0	0
T.v. one Sat	−3	5	−	−
T.v. two Sats	−3	5	−3	5

Study cases for the multi-satellite visibility
Table 1

4 Study Case 2: S-CDMA Based DAB System

A possible application of the S-CDMA and Rake demodulator is in a mixed, satellite and terrestrial Digital Audio Broadcasting System (DAB). In this case, the Rake receiver will greatly improve the system efficiency by exploiting the additional reception diversity offered terrestrial re-transmitters covering satellite shadowed areas. We will assume as system baseline the utilization of a constellation of satellites in Highly Elliptical Orbit [5]. With the selected type of orbit, elevation angle is better than 60° will be provided to the majority of mainland Europe. The geostationary orbit is also reported here as reference case. The overall system architecture, sketched in Fig. 7. Several coded Direct-Sequence Spread-Spectrum (DS-SS) signals carrying audio programs originated in different studios, are synchronously CDM multiplexed in the Feeder Link Station (FLS) modulator. Rate 3/4, $k = 7$ convolutional coding and direct sequence QPSK modulation has been finally selected as trade-off between power and bandwidth efficiency. Many FLS's up-link their DAB programs to the operational HEO satellites (or to the single GEO satellite). In case of multiple access in the satellite up-link, different CDM signals coming from various FLS are multiplexed in CDMA mode at the satellite transponder input. In this situation, in order to minimize the co-channel interference, all the FLS's sharing the same frequency band shall be synchronized in time and in frequency. The satellite acts as a transparent transponder and broadcasts the signals toward the earth where they are received by mobile, portable and fixed users at L-band. The terrestrial single frequency gap-filler network retransmits the DAB signals at the same satellite carrier frequency over highly shadowed (urban) areas. In our case the overall capacity results to be limited by the terrestrial SFN co-channel interference, hence the coding gain can be more relevant than the asymptotic spectral efficiency. Additional performance improvement in the multipath dominated urban environment is achieved by using the Rake receiver.

4.1 Channel Modeling

The fading model for the wideband satellite mobile channel, is a simple extension of the one discussed in [6]. Line-of-sight signal shadowing is modeled as a multiplicative lognormal process with mean μ_{LGN} and standard deviation σ_{LGN}. The instantaneous multipath results from the sum of several reflected rays, each of them characterized by a different amplitude, phase and delay with respect to the line-of-sight component [2]. It has been found that a single delayed ray model, with equivalent average power and Rayleigh fading superimposed, is sufficient for an accurate modeling of the multipath interference in the CDM system under study and that the associated delay is not critical when greater than $2 \div 3$ chips. For the cellular terrestrial network a regular structure has been assumed like in [6]. For symmetry reasons the user locations are referred only to a portion of the cell. A complete block diagram of the terrestrial channel is depicted in Fig. 8. We will assume that the envelope of each cell signal received at the mobile side will be affected by independent zero

Table 2 : Rate 3/4, k=7 CCQO-QPSK-CDM BER performance @ BER=10^{-3},14 channels, $T_b/T_C = 20.6$

Case	C/M (dB)	μ_{LGN} (dB)	σ_{LGN} (dB)	$[\overline{E}_b/N_0]_{req}$ (dB)
AWGN	∞	0	0	3.9
HEO/LGA	10	-3	2	6.7
HEO/HGA	12	-3	2	6.4
GEO/HGA	7	-6.5	3	12.3

mean lognormal process with 8 dB of standard deviation, and a path loss proportional to the inverse of the fourth power distance [6]. Another important issue in modeling the UHF terrestrial urban channel is the time variant delay distribution characterization. For our particular network of terrestrial retransmitters broadcasting the same CDM multicarrier signal, we simply assume that all the signals multiplexed in CDM coming from the same cell carrier are chip and symbol synchronous[1], while any pairs of signals coming from different cell locations are chip asynchronous (i.e. the differential delay is assumed to be greater than one chip).

4.2 DAB System Performances

The basic modem design principle and detailed analysis is reported in References [1], [7].

In Table 2 simulation results for the satellite channel utilizing rate 3/4, $k = 7$ CCQO-QPSK-CDM system are summarized. The terrestrial system is complementary to the basic satellite broadcasting system as it is intended to provide good service quality in highly populated urban areas where, even using HEO, the line-of-sight signal is often lost. In this case, a Single Frequency Network (SFN) of cellular repeater transmitting at the same satellite carrier frequency can operate as gap-filler. The SFN simulator used consists of a regular 19 cells structure, where each cell transmits a CDM signal received at the user location with its relevant geometric path loss and lognormal shadowing. To keep the simulation time within acceptable limits, the coded symbols are PSK modulated but not spread by the Gold sequences. Effect of CDM self-noise is taken into account at the receiver side by injecting a non-stationary Gaussian noise level corresponding to the instantaneous interference level at the despreader output. Soft signal combining at the symbol matched filter output is suboptimally performed. Instantaneous signal rays amplitude is used by the equivalent self-noise generator to compute the self-noise level. Figure 9 show the the worst-case user location simulated BER of the terrestrial network versus the spectral efficiency, i.e. the channel loading, for the three fingers and single finger Rake receiver. Performance analysis in the coded case can not be easily performed because of the non-stationary noise samples statistics at the Viterbi decoder input due to signal and interference shadowing. It can be observed that, for a target worst-case BER of 10^{-3}, by using rate 3/4 CCQO-QPSK-CDM, one can achieve SFN spectral efficiency of about 0.6 b/s/Hz, a value comparable to the satellite channel capacity. Rate 1/2 CCQO-QPSK-CDM does not provide any appreciable SFN efficiency improvement. The three fingers Rake receiver allows a considerable capacity gain both for the coded and the uncoded system, ant its performance results about two times better than the single finger Rake receiver.

[1] By simulation it has been shown that by synchronizing at chip/symbol level the cell signals, a doubling of the overall SFN capacity can be achieved.

5 Summary and Conclusions

In this paper we have analyzed the behaviour of S-CDMA in frequency-selective channels, providing an handy-to-use formula for evaluating the system bit error rate based on a Gaussian co-channel interference approximation. In the second part we have presented two study cases to illustrate potential adavnatges provided by the Rake receiver diversity exploitation on the receiver performance. Results of study case one show that when two satellites are constantly in visibility (static case) the interference situation worsens and a only a limited improvement can be achieved through combining. Different is the case with the user experiencing two satellites in visibility but with two independently shadowed channels. In this case the Rake receiver diversity exploitation is a clear premium in terms of capacity and service availability. The same conclusions apply to the case of a satellite DAB system with terrestrial gap-filler single frequency network. Once more consistent diversity gain is achievable on the terrestrial SFN where many independently faded signals with different delays are available at the demodulator input.

References

[1] R. De Gaudenzi, C. Elia, R. Viola, *"Band-Limited Quasi-Synchronous CDMA: A Novel Satellite Access Technique for Mobile and Personal Communication Systems"*, IEEE J. on Sel. Areas in Comm., vol. 10, no. 2, Feb. 1992.

[2] G.L. Turin, *"Introduction to Spread-Spectrum Antimultipath Techniques and their Applications to Urban Digital Radio"*, Proc. IEEE, vol. 68, pp. 328-353, March 1980.

[3] Z. Xie, R.T. Short, C.K. Rushforth, *"A Family of Suboptimum Detectors for Coherent Multiuser Communications,""* J. Sel. Areas in Comm., vol. 8, pp. 683–690, May 1990

[4] C. Loo, *"A Statistical Model for a Land Mobile Satellite Link,"* IEEE Trans. on Vehic. Techn., vol. 34, August 1985.

[5] P. Lo Galbo et al., *"ESA Personal Communications and Digital Audio Broadcasting Systems Based on non-Geostationary Satellites"*, IMSC-93, session on DBS and Enhanced Services.

[6] K.S. Gilhousen, I.M. Jacobs, R. Padovani, L.A. Weaver, *"Increased Capacity Using CDMA for Mobile Satellite Communications"*, IEEE J. on Sel. Areas in Comm., vol. 8, no. 4, May 1990.

[7] R. De Gaudenzi and F. Giannetti, *"Analysis of an Advanced Satellite Digital Audio Broadcasting*

System and Complementary Terrestrial Gap-Filler Single Frequency Network," submitted to IEEE Trans. on Vehic. Tech., November 1992.

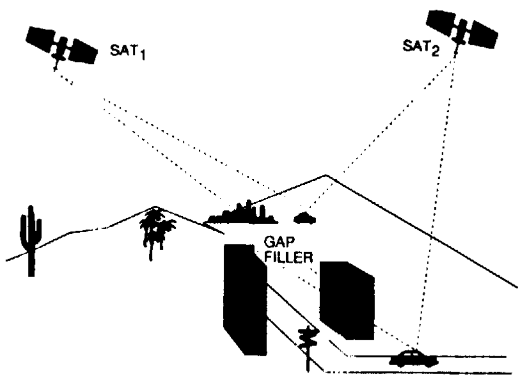

Figure 1: Satellite diversity and gap transmitters for increased availability quality

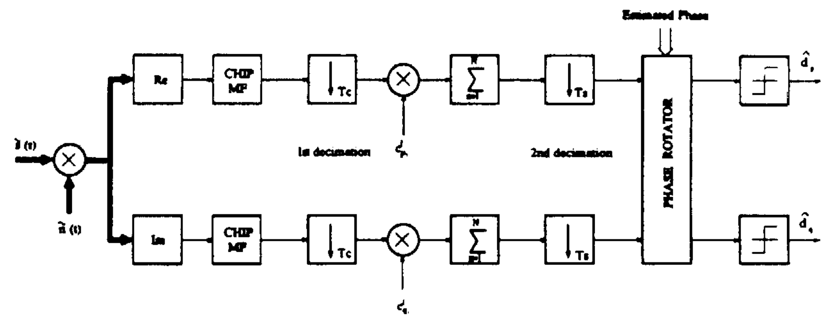

Figure 2: I-Q DS/QPSK demodulator block diagram

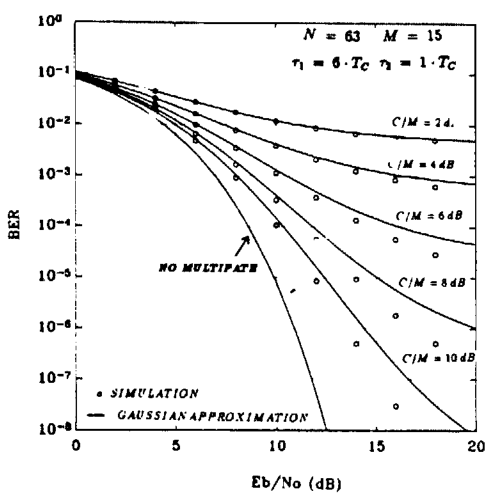

Figure 3: BER vs. E_b/N_0, static channel

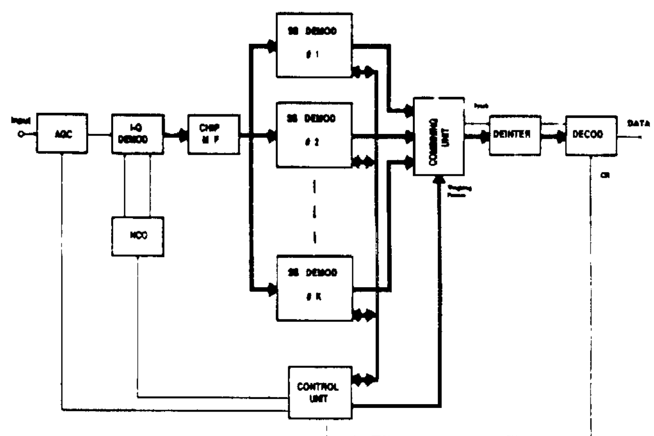

Figure 4: K-paths Rake receiver block diagram

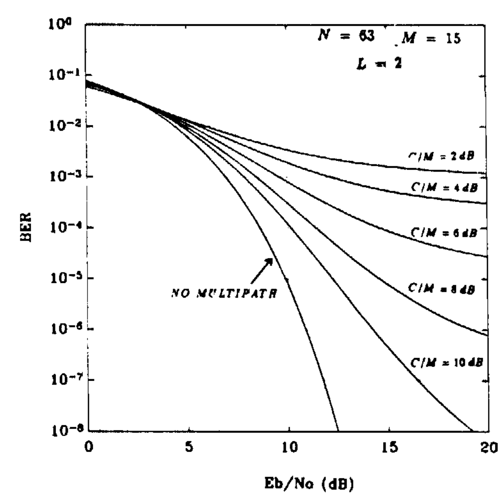

Figure 5: Rake performance in the static channel

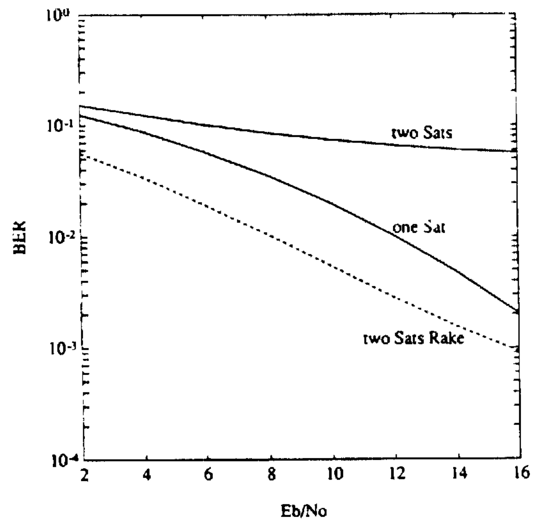

Figure 6: Performance in the Multi-Satellite channel

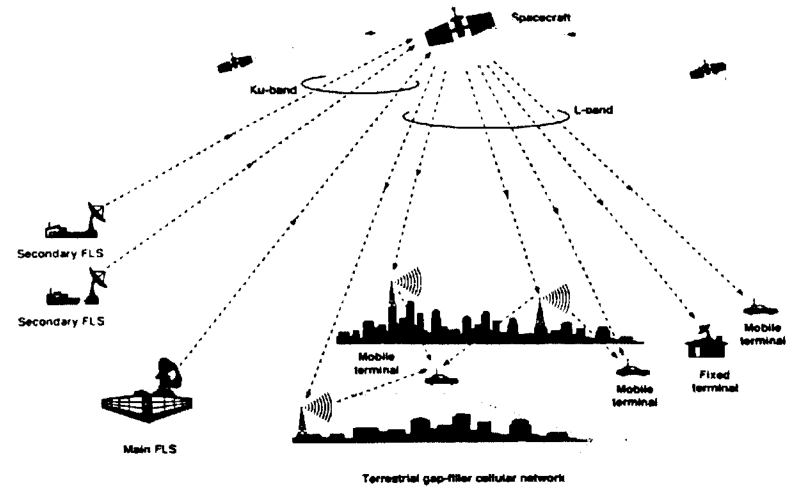

Figure 7: S-CDMA DAB System Architecture

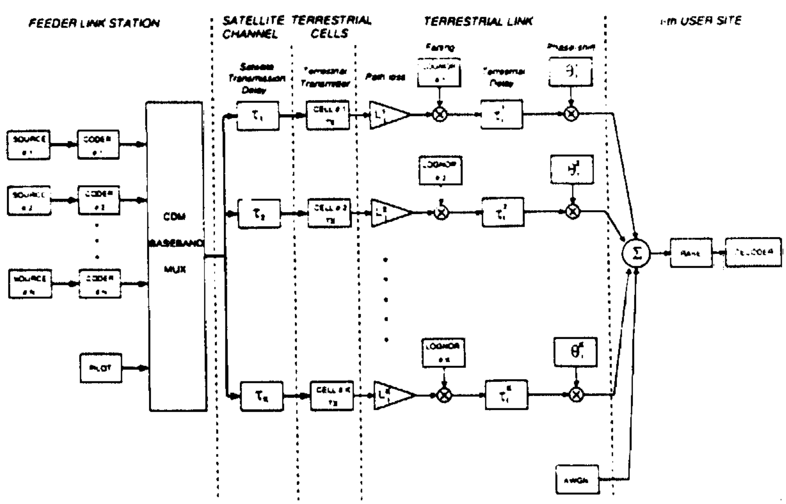

Figure 8: Terrestrial Channel Block Diagram

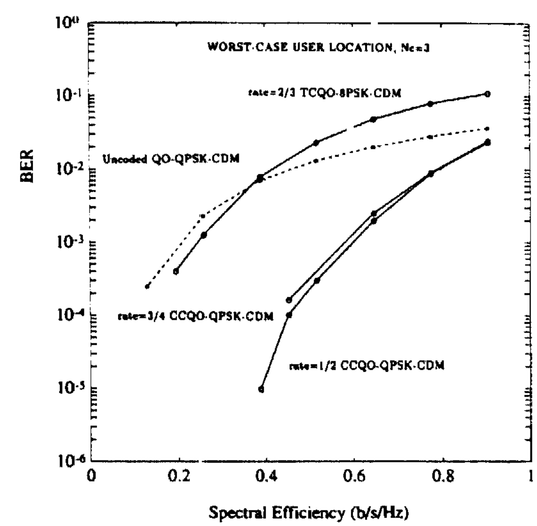

Figure 9: BER versus Spectral Efficiency (worst case)