Telecommunication Systems

Code Division Multiple Access Schemes for Terrestrial and Satellite Mobile Communication Networks: Modeling and Performance Evaluation (1)

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Abstract. This paper deals with the modeling and performance evaluation of different Code Division Multiple Access schemes suitable for applications in terrestrial and satellite mobile communication networks. The use of particular propagation channel models and the relative sensitivity of different demodulation schemes to their parameters are the subject of the paper. In particular, an extension to the case of wideband communications of Lutz's satellite channel model is presented. The main goal is to analyze how the increased interference level, typical of a multipath environment, can influence different demodulator architectures in different propagation conditions. Perfectly coherent and differential modulation methods are employed with conventional and RAKE receivers to derive the error rate performance by computer simulations. Some issues concerning the characterization of the propagation channel models in the case of the RAKE receiver are also investigated and discussed.

1. INTRODUCTION

Mobile communications is one of the fastest growing sector of the telecommunications industry. A clear measure of its vitality is the huge effort currently underway to develop the second-generation of digital mobile radio systems on the heels of the stunning success of their first-generation analog counterparts.

Part of the development effort is aimed at enhancing the efficiency of wireless networks to serve increasing numbers of users and broader coverage areas, while providing reliable links whatever the channel propagation conditions. Needless to say, this arduous task can only be accomplished by combining extremely sophisticated technologies and architectures. A recent architectural proposal (termed "mixed cell architecture" [1]), possibly interconnected to a satellite network covering vast areas of land, sea, and air, seem to be a valid solution to flexibly cope with extremely complex and variable traffic flows. The communication system to meet these requirements affords perfect integration of the various hierarchy layers, while providing enhanced user capacity and call quality regardless of the hostility of the environment.

Code Division Multiple Access (CDMA) is a prime candidate for a future multiple access scheme in a global wireless network. It can be shown that, taking advantage of the interference reduction induced by some techniques such as multibeam or multisected antennas and voice activation, CDMA is able to increase capacity with respect to FDMA and TDMA [2-5]. However, these considerations contrast sharply with those of Turin who investigated the effects of the mobile radio propagation channel on an asynchronous CDMA system [6]. According to Turin, the environmental characteristics where the mobile link is established have a "multiplying" effect on multiple access interference, thereby sometimes resulting in an unacceptable quality degradation of the received signal. Such a disagreement shows that further results are needed to really consider CDMA a competitive technique in a global mobile radio network environment.

Discussions of CDMA performance in the frequency-selective fading channels typical of mobile links have regularly appeared in the literature [7-10]; unfortunately, however, they all share the drawback of involving sophisticated, and sometimes approximate, mathematical approaches that are unwieldy when nonlinearities and imperfect filtering or timing must be considered. Therefore, in order to evaluate true effectiveness, computer-aided modeling is the only practical approach to carry out in deriving the performance of CDMA communication systems in a simple and quick way.

This paper is concerned on the performance evaluation of different CDMA schemes in satellite and terrestrial mobile fading channels on the basis of simulation results obtained using the Comdisco system SPW soft-
ware on a UNIX platform. Of note is the special care taken with modeling of the propagation channels in order to simulate actual operating conditions as closely as possible. In evaluating the symbol error probability at the mobile unit of a synchronous CDMA system [11], different types of propagation channel, and different alternatives for the mobile demodulator implementation, such as perfectly coherent, differential and RAKE demodulation, have been considered.

The paper is divided into the following sections: After the Introduction (section 1), section 2 provides an expression for the transmitted signal, relating it to the structure of the transmitters and the CDMA system parameters. Section 3 illustrates the channel models for mobile satellite and land communications. Section 4 describes the receiver model in coherent and differential forms. Section 5 provides the performance analysis. Section 6 evaluates the effectiveness of a simple RAKE demodulation algorithm and deals with the problems concerning the computer simulation of such a system. Section 7 presents the conclusions.

2. TRANSMITTER MODEL

In this section, the transmitter model in the case of a quaternary (QPSK and differential QPSK) spread spectrum direct sequence system is defined. Let us consider the situation of active transmitters at the base station. Focusing on a particular mobile receiver, only one of the active radios transmits information intended for the receiver, while the other active radios produce undesirable interference.

Under these assumptions, referring to Fig. 1, the complex envelope of the signal transmitted by the base station (satellite or terrestrial) can be defined as [11]:

\[
S(t) = \sum_{k=1}^{M} \sum_{l=-\infty}^{\infty} \left( j^{\cdot} c^{1}_{p,l} d^{1}_{p,n} g_{T}(t-iT_{c}) + j^{\cdot} c^{1}_{q,l} d^{1}_{q,n} g_{R}(t-iT_{c}) \right)
\]

where:

- \( | \cdot | \) denotes the modulus \( N \)
- \( \{ \cdot \} \) denotes the integer part of \( \frac{\cdot}{N} \)
- \( d^{1}_{p,n} \) is the sign of the \( k \)-th user \( n \)-th in-phase transmitted symbol
- \( d^{1}_{q,n} \) is the sign of the \( k \)-th user \( n \)-th quadrature transmitted symbol
- \( c^{1}_{p,h} \) is the sign of the \( k \)-th chip for the \( k \)-th user in-phase spreading sequence
- \( c^{1}_{q,h} \) is the sign of the \( k \)-th chip for the \( k \)-th user quadrature spreading sequence
- \( T_{c} \) is the chip duration
- \( g_{T}(t) \) and \( g_{R}(t) \) are information sequences in the case of coherent QPSK, whereas for differential QPSK they are differentially encoded version of information sequences [12].

The spreading sequences belong to the preferentially phased Gold codes having quasi-orthogonal cross-correlation properties in synchronous systems (i.e., systems having a synchronization of the spreading sequences at chip level) [11]. We assume that the spreading sequences in each data pulse are formed by \( N \) pulses and the period of the spreading sequences is \( NT_{c} \). The use of different spreading sequences for in-phase and quadrature signals is needed to cope with the problems arising from the presence of amplifier nonlinearities, imperfect carrier phase recovery, and any other phenomenon carrying a part of the in-phase component into the quadrature and vice versa.

All frequency and timing inaccuracies at the transmitter and receiver have been neglected, since an analysis of their effects would be beyond the scope of this paper.
3. CHANNEL MODEL

Land-mobile satellite channel

Satellite communications with land mobile terminals are plagued by severe degradation due to signal shadowing and multipath fading. Shadowing is the attenuation of the direct path, i.e. line-of-sight (LOS), over the total signal bandwidth caused by trees, buildings, hills, and mountains. The process, which may be explained in terms of absorption, diffraction, and scattering, is strongly dependent on the signal path length through the obstacle, the type of obstacle, the elevation angle of the satellite with respect to the position of the mobile unit, the direction of travel, and carrier frequency [13, 14].

Multipath fading is due to the so-called signal diffuse component defined in [14]. The signal, transmitted from a satellite, illuminates obstacles in the vicinity of the mobile unit, which results in reflected energy emanating from multiple scatterers. Waves from these scatterers vary randomly in polarization, amplitude, and phase according to the nature of the scatterer and different propagation distances. In addition, every wave shows a Doppler frequency shift proportional to the relative speed between any scatterer and the vehicle.

As the vehicle moves from one location to another, most of the propagation characteristics vary, resulting in different shadowing conditions and a nonstationary statistical character of the received signal. Due to their relative slowness, the environment characteristic variations may be considered constant within a small area. Hence, in modeling channel propagation effects, we can identify typical environment categories, build their relative models, test our communication systems separately, and thus draw conclusions about their adaptability to different operating conditions.

Other effects on the link such as Faraday rotation, ionospheric scintillation, and the presence of a signal component reflected from the ground in the direction of the satellite, vanish in relation to particular carrier frequencies (L band) or antenna radiation patterns [14].

Due to the time-varying behavior of the land mobile satellite link, the introduction of a fade margin into the link budget is often insufficient, meaning that an accurate carrier recovery, bit timing, and frame synchronization have to be adopted. All these conditions have been assumed as satisfied in our analysis.

A statistical propagation channel model for land mobile satellite communications, based on narrowband measurements at a single frequency, was developed by Lutz et al. [15]. Two distinct propagation link states are considered: shadowing and no shadowing.

When there is no shadowing, the mobile unit receives the superimposition of the direct wave and constant intensity (power) multipath echoes. The total received signal amplitude forms a Rice process and the probability density of the instantaneous received power \( P \) has the form:

\[
f_{\text{RICE}}(P) = Ke^{-K(P+1)}I_0\left(2K \sqrt{P}\right) \tag{2}
\]

where \( I_0 \) is the modified Bessel function of zero order and \( K \) is the ratio of LOS to average multipath power, assuming unitary LOS power, i.e. the power of the unobstructed satellite link is normalized to unity.

With shadowing, a totally obscured LOS is assumed. The mobile unit receives only multipath components resulting in a Rayleigh statistics. The received power has the following distribution:

\[
f_{\text{RAYLEIGH}}(P) = \frac{1}{S} e^{-\frac{P}{S}} \tag{3}
\]

where \( S \) is the average multipath power lognormally distributed as follows:

\[
f(S) = \frac{10}{\sqrt{2\pi} \sigma \ln 10} e^{-\frac{(10\log S - \mu)^2}{2\sigma^2}} \tag{4}
\]

where \( \mu \) is the mean power level decrease (in decibels) and \( \sigma^2 \) is the variance of the power level due to shadowing. The process associated to the lognormally distributed average multipath power is usually slow time-varying. In our analysis, it is kept constant, since the resulting simulation time is too short to properly take into account the variations. As mentioned previously, every contribution from multiple scatterers to the multipath signal is shifted in frequency by an amount proportional to the relative speed between any particular scatterer and the mobile unit. Summing all the components, we observe a form of frequency spreading in addition to a frequency distortion. The maximum Doppler shift, termed fade rate [14], is closely related to the dynamics of fading. Typical values in L band and for the velocity of the mobile unit less than 100 km/h range between 100 and 200 Hz [15, 16].

The model proposed by Lutz et al. reproduces the probability density function of the received signal power as well as the dynamic behavior of the fading and shadowing processes, but its applications are limited to the analysis of systems where the bandwidth of the transmitted signal is small compared to the coherence bandwidth of the channel. Under these conditions, the concept of multiplying fading [17] can be applied, so the received signal is the transmitted signal multiplied by a complex (Rice or Rayleigh distributed) fading process. Lutz et al. show that the model may be used only for signal bandwidths up to several tens of kHz. This section deals with a suitable extension of the channel model given in [15] to the case of wider transmission bandwidths.

Let us assume that in the spread spectrum systems under consideration, a chip time small enough for the delay spread of the channel or, equivalently, a transmission bandwidth wide enough for the coherence bandwidth is used. Under these conditions, the channel becomes frequency-selective and a multipath time discrimination capability is possible at the receiver. By means of the properties of code crosscorrelation, two multipath signal components separated by at least one chip time, can be resolved, while distinct paths in the physical me-
medium whose propagation time difference is smaller than one chip time cannot be distinguished, thereby merging into a single frequency-nonselective fading signal.

The impulse response of the channel, as also illustrated in [18], is given by:

$$h(t) = \sum_{k=1}^{L} a_k e^{j \theta_k} \delta(t - \tau_k)$$

(5)

where $a_k$, $\tau_k$, $\theta_k$ are the gain, time delay, phase of the $k$-th path respectively and $\delta(\cdot)$ the Dirac function.

Assuming an unshadowed situation, the first received path is described by (2).

The superimposed multipath is due to the components coming to the receiver within a chip time after the arrival of the direct path. The other paths resulting from multipath contributions with propagation delays, with respect to the direct path arrival time, greater than one chip time, are accurately described by a Rayleigh path gain distribution and uniformly distributed phase.

The parameters of the various paths can be found if the power delay profile [17] is known. In [9] the power delay profile is considered:

$$P(\tau) = \frac{1}{\Delta} b e^{-\frac{\tau}{\Delta}}$$

(6)

where $\Delta$ is the delay spread, $b$ the total multipath power and $\tau$ the time variable. The power of path $k$ can be approximated as:

$$b_k = b \left(1 - e^{-\frac{\tau_c}{\Delta}}\right) e^{\frac{(k-1)\tau_c}{\Delta}}$$

(7)

The multipath power superimposed on the direct path is reduced with respect to the case of conventional narrowband transmission. The rest of multipath power is distributed, according to (7), among a number of resolvable paths approximately equal to:

$$L = \left\lfloor \frac{\Delta}{\tau_c} \right\rfloor$$

(8)

where $\lfloor x \rfloor$ is the integer part of $x$.

**Simulator architecture**

We shall start by describing the structure of the land mobile satellite channel model used in our test. Taking into account typical values of delay spread (measured in land mobile channels) [18] and the system transmission bandwidth, a three paths model seems a reasonable choice; in section 5 numerical values of the system under consideration will justify the choice.

In the unshadowed condition, the first path gain has a Rice distribution, while the others are Rayleigh distributed. In the case of a completely obstructed LOS, energy propagation is largely by way of scattering, and all three path gains are Rayleigh distributed.

Referring to the results in [15] for the statistics of the recordings made for different satellite elevations, types of environments, and antennas, we set three typical propagation cases:

- **Good** $K = 14$ dB corresponding to a propagation link in an open area, free from large obstacles able to obscure the direct path, and with a relatively small number of scatterers responsible for the multipath.

- **Medium** $K = 5.5$ dB corresponding to a propagation link in weakly shadowed areas or in dense scatterer areas.

- **Bad** $K \rightarrow -\infty$ totally shadowed direct path, typical of densely populated urban areas.

The heart of the channel model is the Rayleigh multipath fading simulator. Each path has a proper simulator independent of the others (Fig. 2). In addition to a proper frequency nonselective multipath simulator, the paths are characterized by a propagation delay and attenuation.
represent the propagation environment associated to un-
shadowed conditions, the direct path between the satel-
tele and the mobile antenna must also be considered.

Fig. 2 shows that, in the multipath fading simulator, the
 technique used is that of [19] with two independent
Gaussian low-pass noise sources with identical spectra
as real and imaginary parts of the complex fading pro-
cess. The simulation of the fading spectrum appropriate
to mobile radios is obtained by properly shaping the
spectrum of the noise sources. For an omnidirectio-
antenna and for urban and suburban land communication
channels, the theoretical spectral density of the complex
envelope of the received signal is given by [20]:

$$S(f) = \begin{cases} \frac{E^2}{2\pi f_D} \sqrt{1 - \frac{(f/f_D)^2}{2}} & |f| \leq f_D \\ 0 & \text{otherwise} \end{cases}$$

(9)

where $E$ is the root mean square (rms) value of the signal
envelope and $f_D = V/\lambda$ is the Doppler shift corres-
dponding to a vehicle speed $V$ and a carrier wavelength $\lambda$ .

Even though (9) has been obtained in [20] for land
mobile radio environments, Vuetic et al. and Lutz et al.
agree in defining the shape of the fading spectrum as a
sharply bandlimited with maximum power at the edges.
Field measurements [16] have shown that the effect on
an unmodulated carrier, whose power density is an im-
pulse, is spreading and a distortion of the spectrum,
which results in a frequency shaping that is accurately
represented by the action of the Rayleigh multipath fad-
ing simulator with shaping filters suggested by Arre-
dondo in [19]. At this point, the similarities between a
propagation model for satellite and land mobile radio
channel start to show up.

In our model the shaping filter is a 13-th order IIR fil-
ter. In Fig 2, the shaping filter is followed by a quadra-
tic interpolator that has the task of making compatible
the sampling frequency of the transmission system with
that of the complex fading process.

The fading rate, or temporal variation rate of the sto-
chastic process in the complex fading process genera-
tion, is regulated by the interaction between the filter
and the interpolator according to the maximum Doppler
frequency and the transmission rate of the communica-
tion system, by interpolating three adjacent samples
with a parabolic curve. Such a simple approach has
been found to be, for our aims and considering the large
interpolation rates, a good compromise between accu-
rate interpolation and simulation time saving.

**Land mobile channel**

Radio propagation in the land mobile radio environ-
ment is described by a highly dispersive multipath
caused by reflection and scattering. Similarly to what
happens in satellite systems, the reflection, refraction
and scattering of radio waves by obstacles of different
natures cause the transmitted signal to reach the mobile
unit by more than one path. All the contributions com-
bine at the receiver to produce a distorted version of the
transmitted signal.

If we consider the receiver motion and the Doppler
effect associated to each wave, the channel must neces-
sarily be described as time variant. The effects observ-
able on the received signal may be expressed in terms
of superposition on two different phenomena [21]:

- A slow fading component, mainly due to local
topographic conditions, antenna height, and other
environmental conditions, whose statistics can be
assumed to be of the log-normal type. As the time
variations of this fading component are relatively
slow, we haven’t taken them into consideration in
the realization of our land mobile channel model.

- A fast fading component (multipath fading) due to
reflections from obstacles and mobile receiver
movement. While for narrow-band transmission,
the multipath medium causes fluctuations in the
received signal amplitude and phase (modeled by
a multiplying complex gaussian fading process as
explained in [17]), if wideband signaling is used,
not all the frequency components of the transmit-
ted signal are influenced by the channel in the
same manner and consequently a series of delayed
and attenuated echoes can be observed at channel
output [22]. Being replicas of the same informa-
tion signal over independently fading channels,
the transmission paths produce a diversity effect
because not all of them tend to fade together.

In addition to these effects, another characteristic of
the land mobile propagation is power decadence with
distance as the inverse of the fourth power [4]. Howev-
er, since this is irrelevant for our aims, it is not contem-
plated in the channel model.

As readily observed, the situation is in every aspect
similar to that of the satellite mobile channel model
described in the previous section. Consequently, on
the one hand, the theoretical assumption about the exten-
sion of Lutz’s narrowband model to the case of wide-
band transmission may be considered substantially cor-
correct, while, on the other, we may have a unique simula-
tor architecture for the two propagation channel models.

The model parameters used in our test are taken from
[23], where different propagation environment and the
simulation solutions are proposed for testing communi-
cation systems to be used in GSM mobile radio network.
Even if the model is normally used with GSM transmis-
sion parameters, a properly chosen transmission band-
width of our spread spectrum system can make the mod-
el frequency selective. As suggested in [24], we set our
transmission bandwidth to 4 MHz to have a sufficient
temporal discrimination of the channel response. In this
way, all the paths prescribed by [23] are resolved, and
we can again express the channel impulse response by (5). Hence, with the structure of Fig. 2 and using parameters such as number of paths, delays, attenuations, fading spectra given in [23], we have a land mobile channel software model which is realistic, standardized, extremely adaptable to the evaluation of the performance of different spread spectrum solutions and consistent with those used in the analytic approaches of [25, 26].

4. RECEIVER MODEL

Direct sequence spread spectrum receivers are traditionally based on correlation receiver techniques, which are optimal for the reception of spread spectrum signals in the presence of AWGN noise. Overlaid multiple access interference deteriorates system performance in terms of bit error probability: if a synchronous CDMA is employed, multiple access interference may be modeled as a slight increase in AWGN noise level, with the quality of the received signal still quite satisfactory [11]. Under these conditions, CDMA is very competitive with respect to other multiple access schemes. However, considering a propagation link from among the ones described in the previous section, the multipath effect on multiple access interference could deteriorate the bit error probability to the point of making CDMA totally inefficient.

We examined two receiver models: a conventional receiver and a RAKE receiver. The latter, considered only for cases where conventional receiver performance is very poor, is illustrated in section 6.

Referring to (1) and (5), the complex envelope of the received signal can be expressed as:

$$S_R(t) = \sum_{k=1}^{L} \alpha_k e^{j\beta_k} S(t - \tau_k) + \tilde{n}(t)$$

where \(\tilde{n}(t)\) is a complex AWGN process with one-sided spectral noise density \(N_0\).

The assumptions we used to establish systems performance in terms of symbol error probability at the mobile unit operating upon the received signal (10), are:

- The composite signal received from the mobile unit comes from a single base station (satellite or terrestrial). Hence, as is evident from (1), all the multiple access interference signals have the same power level as the intended signal.
- A dedicated service channel provides the mobile unit with the spreading codes.
- A perfect chip synchronization of the incoming signal is achieved by suitable acquisition and tracking procedures on an unmodulated master code [11] or directly on the information stream with or without known training sequences. In all cases, we assumed locking on the first path of the various channel model configurations.

Coherent receiver

The mobile unit is supposed to be able to adjust its timing clock and carrier frequency to provide a perfect phase, bit, and chip synchronization with the first signal multipath component endowed with a significant power level.

As shown in Fig. 3 (where the thick lines represent complex signals), the first step in the demodulation process after baseband conversion is chip matched filtering. The transmit filter of section 2 is defined as a square-root-raised cosine frequency-shaped. The same kind of filter shaping should be used in the demodulator. Theoretically, no detection losses are observed if ideal filters are employed, since the Nyquist criterion is satisfied:

$$\left\{ \begin{array}{l}
g(0) = 1 \\
g(kT_r) = 0 \quad \text{for any integer } k 
\end{array} \right. \quad (11)$$

where \(g(t) = g_r(t) \otimes g_e(t)\) is the resulting channel impulse response (linear AWGN propagation channel case) with \(g_e(t)\) receiver filter impulse response and \(\otimes\) is the time domain convolution operator.

The performance of the CDMA system under consideration has been derived in the case of a linear AWGN propagation channel case with real square-root raised-cosine shaping filters with a roll-off factor \(\beta = 0.5\). In comparing the symbol error probability with that of the rectangular-shaped chip, no substantial differences have been highlighted. This means that even if filtering is
recommended for practical applications, we may deal throughout only with the rectangular shaped chip, thereby simplifying modeling and saving computation time.

The next step in the demodulation process is the despreading operation, implemented by means of a correlation between incoming data and local Gold sequences. At the output of the integrator (integrate and dump device), in any given signaling interval, we have the superposition of the information symbol, the filtered AWGN noise, and the multiple access interference. In a generic signaling interval \( s \), the terms make up a decision variable we can call \( V_s \). The last of the three terms comes from the synchronous crosscorrelation contributions plus the crosscorrelation components added by delayed multipath.

**Noncoherent receiver**

In the case of a rapidly time-varying multipath fading channel, carrier phase recovery may be a difficult task. Efficient acquisition and tracking procedures, capable of following the fast-changing channel complex impulse response phase, are feasible but of extremely complex realization. In order to reduce the cost of the mobile receiver, noncoherent data demodulation may be performed.

If a QPSK modulation scheme and a direct sequence spread spectrum technique are used, the choice inevitably falls on the differential demodulation.

The differential QPSK receiver requires only that the phase of the signal component it locks onto does not change over the duration of two adjacent symbols. Fig. 4 highlights that the differential demodulation process is similar to the coherent one. Obviously, the baseband conversion is achieved noncoherently.

\[
\Delta_s = V_s V_{s-1}^* 
\]

where \( V_s \) is the despreader output at signaling interval \( s \), \( V_{s-1} \) is the despreader output at the signaling interval \( s - 1 \), and * is the complex conjugate operator.

The results in [17] for DPSK modulation in the light of the conclusions regarding synchronous multiple access interference in [11] may be adapted to provide a theoretical analysis of symbol error probability of a synchronous DQPSK-CDMA system in a linear AWGN propagation channel. Even though a degradation in system performance is to be expected, we can assume that, under ideal conditions and for a linear AWGN propagation channel, a synchronous DQPSK-CDMA system is still able to guarantee high performance.

**5. Simulation Results and Considerations**

It is well known that CDMA is an exceedingly competitive multiple access scheme capable of reaching the highest theoretical number of simultaneous users with an acceptable signal quality, provided synchronization at chip level is maintained.

Using computer simulation, we shall now verify if this consideration is still valid in multipath fading propagation channel environments of various types.

For each test, a random symbol information stream is generated, which thereafter enters the channel simulator and zero mean, white gaussian noise is added to the faded signal at output. The detection process is then performed to estimate the transmitted information stream from the faded received symbols. Lastly, the symbol errors are counted to obtain an estimate of the symbol error rate performance for a given value of \( E_b/N_0 \). Since channel coding and interleaving procedures are missing and since voice communication is the system’s primary application, a symbol error probability between \( 10^{-2} - 10^{-3} \) can be considered acceptable.

**Land-mobile satellite channel**

The propagation channel model architecture and a set of parameters have been described in section 2. The simulation test is based on a spreading sequence set of 31 chip preferentially-phased Gold codes, working at a chip-rate of 750 kchip/s, which approximately corresponds to a source bit rate of 50 kbit/s. The channel Doppler frequency is set at \( f_D = 150 \) Hz, while the power delay profile [17] is maintained on significant levels for approximately 4 ms. For the last two parameters, a better approach would have been to assign different values for different environmental conditions in the model, but, owing to the lack of standard measurements, any theoretical position about precise values appears questionable; therefore we set them to average, i.e., plausible fixed values, preferring to differentiate the various propagation conditions only by the parameter \( K \) as explained in section 2. However, we feel that, parameters \( K \) being equal, small variations in channel Doppler frequency or multipath delay spread would affect spread...
spectrum system performance only in a limited way.

Coherent receiver

With the channel phase of the first path assumed as perfectly recovered, the principal impairments are the combination of the Rice first useful path amplitude fluctuation and the delayed multipath contributions, which adds asynchronous crosscorrelation components to the synchronous multiple access interference.

GOOD channel

The symbol error probability for different operating conditions is illustrated in Fig.5. In addition, the curve relative to a linear AWGN channel is also shown for comparison.

![Fig. 5 - Probability of symbol error vs. $E_b/N_0$ for land-mobile satellite channel GOOD, coherent receiver.](image)

As the extremely long computation time was not conducive to numerous simulation tests, we limited testing to two system load conditions. As can be observed, even with the maximum number of users ($M = 16$) simultaneously present in the channel, system performance degradation is not too large. Hence, we may conclude that, if the mobile terminals are localized in open areas such as highways, railways, and waterways, the considerations expressed in [2] about greater capacity of the CDMA scheme with respect to FDMA are fully justified.

MEDIUM channel

The MEDIUM channel is shown in Fig. 6, together with the BAD channel condition and a curve of the GOOD channel condition for comparison. A net performance degradation with respect to the GOOD channel and an error floor for high $E_b/N_0$ values clearly emerge. The use of an interleaver to break up burst errors longer than one symbol (noted in the error configuration) is recommended to allow successful operation of the decoder for the associated channel coding procedure.

Hence, when the mobile user operates in a more complex environment (in rural or suburban areas with roads surrounded by trees, houses, or small buildings), CDMA is still advantageous if a powerful combination of channel coding and interleaving procedure is achieved.

BAD channel

A BAD channel results when the mobile unit is embedded in a very hostile environment where all communication systems have notable operating problems. The direct path is completely obscured and the receiver is obliged to work with the weak multipath components that reach it.

The situation is illustrated in Fig. 6 where an irreducible high error probability is shown. Presumably, a lower load condition would not be able to improve error performance, because the primary causes of system failure are: 1) the receiver's locking on the first multipath component subject to wide and fast Rayleigh amplitude fluctuations and 2) the presence of asynchronous multipath components with a power level comparable to the first useful path one. The only remedy appears to be system diversity.

Differential receiver

The aim of this section is to evaluate the feasibility of a differential demodulation of QPSK signals for a synchronous CDMA multiple access scheme in a time-variant multipath fading channel and compare its efficiency to the ideal coherent receiver considered in the previous section. The environmental conditions and simulation parameters are the same as those for coherent demodulation. The condition that the channel-introduced random phase be constant over the duration of two adjacent symbols is due to the stochastic-process temporal variation rates in accordance with the planned coherence time [17] or maximum Doppler frequency. This can be veri-
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fied by a simple look at the channel simulator output.

**GOOD channel**

The system behavior is illustrated in Fig. 7. By adding 3 dB to the $E_b/N_0$ value, it is possible to achieve the same performance as the coherent receiver. Therefore, even with a simplified receiver, synchronous CDMA is a reliable and efficient multiple access scheme in open areas link.

![Fig. 7 - Probability of symbol error vs. $E_b/N_0$ for land-mobile satellite channel GOOD, differential receiver.](image)

**MEDIUM channel**

As shown in Fig. 8, the full-loaded system with a heavier multipath is unable to operate correctly. However, it is unlikely that channel coding and interleaving techniques could improve system performance at such conditions. Presumably, the asynchronous interference deriving from multipath delayed contributions "saturates" the more sensitive to noise differential demodulation system. Hence, we can deduce that, under more "difficult" propagation conditions, a synchronous DQPSK-CDMA scheme can operate correctly only for a low traffic flow.

**BAD channel**

No analysis was performed for the BAD channel, since negative behavior was foreseen.

**Land mobile channel**

As described in section 2, the land mobile channel simulator architecture is the same as the land mobile satellite channel architecture. The parameters are now in accordance with the guidelines in [23]. We chose Urban Area and Rural Area from among the propagation conditions proposed in [23] with a common maximum Doppler frequency $f_d = 100$ Hz and used a spreading sequence set of 127 preferentially phased Gold codes operating at a rate of 4 Mchip/s. It should again be pointed out that at this transmission rate, all the paths planned in the channel model are resolved. The larger number of chips in an information symbol translate into an increased system complexity and also increase simulation computation time.

The results are summarized in Fig. 9. Even with a low traffic flow ($M = 9$ users of 64 possible) the coherent receiver does not perform well in the Urban Area, while an acceptable symbol error probability $P(e) = 10^{-2}$ is achieved in the Rural Area. A differential receiver was also tested, but performance did not prove fully satisfactory.

![Fig. 9 - Probability of symbol error vs. $E_b/N_0$ for GSM channel models.](image)

Hence, we can conclude that, with perfect coherent demodulation and with the reduction in interference induced by the techniques described in section 1, a terrestrial CDMA system is feasible in good propagation conditions. However, to make it support a sufficient traffic flow, which would thus make it competitive with the most recent digital multiple access schemes, some diversity procedure has to be used in order to solve the problem of the propagation channel which constitutes the main impairment of system performance.
6. RAKE RECEIVER

We have seen earlier that, apart from the total shadowed propagation condition, CDMA behaves well for a satellite mobile radio network. However, in a terrestrial application, problems arise due to the heavier multipath presence. As we have already suggested, there are basically two principal causes of system failure: the random amplitude fluctuation of the first path the receiver locks onto and the asynchronous interference deriving from the presence of delayed multipath signal components.

Unless all the codes assigned to the users are known, nothing can be done to solve the asynchronous interference problem, which is an intrinsic characteristic of the CDMA multiple access scheme in multipath channels.

A practical solution to reduce the performance degradations is to use diversity techniques [17].

The RAKE approach is a well known diversity technique which is based upon the time discriminability offered by a wideband spread spectrum system which resolves the multipath components and provides the receiver with several independently fading signal paths.

RAKE receiver scheme

A possible scheme for the RAKE receiver is depicted in Fig. 10. Every demodulator has one chip time-shifted despreading sequences with respect to the adjacent demodulators, so that all received signal components with delays falling into a window of about three chip times can be processed. We suppose that, at the start, the first demodulator locks onto the first strong signal multipath component. The other arms sound a portion of multipath profile, searching, in a temporal fixed window, for signal significant contributions. The signal strength in each portion is measured by an envelope detector, whose output is integrated during a variable time interval to achieve better noise suppression (Fig. 11). In accordance with the envelope measurements, a control unit chooses periodically the best two demodulator outputs to combine them according to an equal gain combining rule to form the decision variable. Such a contribution allows to discard the weakest contribution, which is very likely to be heavily conditioned by noise and interference.

If a very wide bandwidth is utilized, a time discrimination capability sufficient to resolve discrete paths is achieved even using fixed time spacing among demodulators sequences. The main drawback is the high number of demodulators necessary to sound a wide portion of multipath profile. To relax this constraint, only three arms are considered in our approach by taking into account that important signal contributions having small delays are generally more likely than those with larger delays.

Simulation results

Even if the above mentioned RAKE scheme is a feasible, simple and robust scheme, evaluating its effective behavior in the propagation channels saturated by multiple access interference, considered so far, is an arduous task also by computer simulation runs besides being almost impossible by analytical approaches without heavy assumptions.

Simulation results are strongly dependent on the propagation channel characterization. Usually, and as assumed in the previous sections, radio mobile propagation channels can be modeled as particular linear time varying tapped delay lines. Considering a conventional CDMA receiver, the delayed multipath components, whether fixed or not, represent only interference while in a RAKE receiver part of them are exploited as independent signal contributions.

Different configurations may be considered and evaluated:

a) An adaptive RAKE with independent arms able to follow the channel impulse response and a channel model characterized by time varying multipath components delays.

b) An adaptive RAKE with independent arms able to follow the channel impulse response and a channel model characterized by fixed multipath components delays.
c) A fixed time referenced arms RAKE (e.g. the scheme shown previously) and a channel model characterized by time varying multipath components delays.

d) A fixed time referenced arms RAKE and a channel model characterized by fixed multipath components delays.

Option a) corresponds to a "real" situation but its implementation would need accurate evaluation of feasibility of different path-tracking functions for arms time positioning. The results would depend on the technique used to track the time at which the main multipath components are received. Optimization procedures and comparison among different possibilities are currently ongoing activities for a further work.

Option b) has not the same validity as option a). Now the arms of the RAKE would periodically jump from one path to another, according to the power level measurements, instead of following a rapidly time varying propagation profile. Therefore it would have simulated a very complex system with little correspondence to the effective operating conditions.

Option c) would offer a pessimistic outlook as the multipath components would positively contribute to the demodulation process only when synchronized with the RAKE arms. In a real situation a "continuum" of multipath components making the propagation profile is more likely to appear; therefore the fixed time delay referenced RAKE arms would probably have something useful, even if weak and noisy, to demodulate all the time (see the classical approach outlined in [17, chapt. 7.5]).

Option d) has no sense if the fixed multipath time delays are different from the fixed time references of the RAKE arms, and someway predictable results if the delay coincides. However this last statement needs a more detailed discussion.

In our simulation approach we have considered the GSM channel model suggested by [23]. In this model, the time delays associated to each multipath component are fixed. Under this assumption, the most reasonable choice was recognized to be option d) with coincident delays. At first sight the situation could simulate the case of an equivalent adaptive RAKE receiver with a perfect multipath intensity profile estimation, i.e. a perfect time positioning of the RAKE arms with respect to the multipath components; this way, the scheme offers an upper bound to the performance of a very efficient adaptive RAKE receiver in a multiuser CDMA environment. A deeper investigation of the structure used in our analysis tells us that the most important signal contributions are perfectly synchronized with the three fixed time spaced arms of the RAKE, that is, with a proper choice of the transmission bandwidth, or equivalently of the chip duration, and the sampling frequency of the computer simulation process, the demodulators are synchronized with the first, equally time spaced, multipath components. This case simulates the situation where a multipath intensity profile, or equivalently a continuum of multipath components, is sounded with a resolution of , where is the duration of a chip. Therefore, our analysis can be considered as an extension of the results given in [17] to consider the case of a CDMA multiple access environment with well-established and standardized channel model parameters.

Coherent receiver

We suppose that in the two demodulators chosen by the control unit a perfect carrier recovery is performed. The results for the propagation condition Urban Area are illustrated in Fig. 12, where the symbol error rate for the conventional receiver considered in the previous sections is reported for comparison. The performance improvement is evident.

In the case of Rural Area as one can note in Fig. 13, the improvement is not so relevant, but still appreciable and an increase in capacity is possible at the expense of a little increase in system architecture complexity.

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Differential receiver

Every chosen arm performs a differential demodulation before implementing the unity weighted combining. In the Urban Area the system has a very bad behavior, probably due to the presence, in every chosen arm, of strong asynchronous interference that saturates the differential demodulation system. In Rural Area, as illustrated in Fig. 13, the RAKE improvement in performance is almost negligible with respect to the results shown in Fig. 9. The last one is a quite interesting result, if we have to deal with a mobile communication links characterized by a Rice LOS propagation path, even in presence of strong delayed multipath components, a differential demodulation scheme and a CDMA multiple access, the real effectiveness of a simple RAKE receiver appears questionable.

7. CONCLUSIONS

In this paper the modeling and performance evaluation of different CDMA schemes suitable for application in both terrestrial and satellite mobile networks have been considered. A suitable generalization of the Lutz’s satellite channel model for wideband communications has been presented. As official extensive wideband measurements have never been performed in the case of land mobile satellite communications, the generalization of Lutz’s model has been developed taking into account qualitative considerations about the similarities between land mobile satellite and land mobile propagation environment.

The aim of the paper was to study the influence of multipath components interference on a synchronous CDMA multiple access scheme from the mobile user point of view. Extensive computer simulation runs of perfectly coherent QPSK-CDMA and DQPSK-CDMA have shown that if the mobile terminal is localized in open areas, system performance degradation caused by multipath interference is not too large even for very high load conditions. In particular DQPSK-CDMA seems a good choice for a simple, reliable and efficient with regard to multipath, multiple access scheme.

In more difficult, but not totally shadowed, propagation conditions, QPSK-CDMA is still good, whereas DQPSK-CDMA can operate correctly only for a low traffic.

As far as land mobile communications are concerned, the GSM channel models were used to study the impact of a multipath environment on a terrestrial CDMA system. Because of the heavy multipath presence, system performance is not so good as in the low shadowed satellite communications. The issues concerning a realistic and reliable computer simulation of a RAKE receiver have been discussed. After that, a RAKE algorithm taking into account the above mentioned issues, has been introduced and tested with the GSM channel models; the improvement in the system performance has been reported.

More realistic channel models and more realistic and sophisticated CDMA receivers, conventional or RAKE, are currently under study.

Acknowledgement

The authors wish to thank Ing. Luciano Antola for his useful cooperation during the review and publishing process of this paper.

Manuscript received on November 15, 1993.

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