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# AN EVALUATION OF DIRECT SEQUENCE CDMA FOR FUTURE MOBILE COMMUNICATION NETWORKS

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## Abstract

*In this paper the performance and some of the implementation aspects of a practical mobile radio communications network employing Direct Sequence Code Division Multiple Access (DS-CDMA) are examined. The use of spread spectrum techniques results in a wideband system, thus permitting the potential exploitation of multipath signal energy, and also a means of reducing interference arising from other users of the spectrum. When compared on an equivalent basis with narrowband modulation schemes, it is shown that the resultant wideband system can have a greatly enhanced user capacity.*

*An analytical performance model is developed in order to assess the spectral efficiency of a DS-CDMA communications network. The computer model permits the performance evaluation of various path diversity schemes alongside numerous digital modulation and error correction coding techniques, whilst operating in a mobile radio channel. In order to substantiate the results presented here, novel power control and handoff protocols are also proposed in light of the assumptions made.*

## 1.0: Introduction

The shortcomings of present day mobile communication systems has placed great emphasis on maximizing the capacity, or spectral efficiency, of any future generation networks. Primarily this has resulted in a concentrated effort to develop more spectrum efficient modulation techniques, such that a large user community can be supported within the confinements of the limited radio spectrum allocated to these services. As a consequence, there has been a proliferation of narrowband modulation scheme proposals for planned, and future generation systems. To this end, Europe will soon embark on the commissioning phase of the pan-European digital cellular radio system (GSM), while in the US the Telecommunication Industry Association (TIA) is now establishing a new US digital cellular standard (Digital AMPS) based upon linear modulation.

Recently, and somewhat unexpectedly, there has been renewed interest in the mobile communications industry, and associated government agencies, in the application of spread spectrum techniques to digital cellular radio and advanced wireless technologies, such as, 'Personal Communication Networks (PCN)'. Hitherto, wideband systems were generally regarded as highly unsuitable for cellular networks in view of the large bandwidth requirements versus pessimistic forecasts of the number of available channels. However, recent developments by Qualcomm [1], and others [2], have shown results to the contrary. In addition to enhanced capacity, there is also a promise of reduced infrastructure costs and low cost subscriber equipment.

In order to obtain a greater insight into the benefits of spread spectrum techniques when compared with existing, or proposed, narrowband digital schemes, the spectral efficiency of such a network must be evaluated in terms of number of users per unit bandwidth per unit area. A computer model has been developed at the CCR such that this parameter can be evaluated for different classes of channel model (rural, sub-urban and urban), RF modulation technique (BPSK, QPSK and M-ary), internal diversity architecture (Maximal Ratio, Equal Gain, and Switched Combining), and numerous error correction coding schemes (Block, Convolutional and Trellis). Using this model the trade-off in spectral efficiency versus certain key parameters, which relate directly to the implementation complexity and cost of such a scheme, can be evaluated.

In addition to the spectral efficiency aspects of the system, it is recognized here and elsewhere [3] that any DS-CDMA network requires a robust power control mechanism if it is to operate in a 'real' mobile radio environment. It is proposed here that the power control sub-system is an integral part of the network handoff protocol. This aspect of DS-CDMA network architecture design is also discussed in this paper.

## 2.0: An Overview of DS-CDMA Cellular Systems:

Unlike conventional narrowband cellular systems, where either Frequency or Time Division Multiple Access (FDMA or TDMA) schemes are employed, in CDMA spread spectrum networks all users share the same frequency/time continuum [4]. The narrowband digitised message from a DS-CDMA user is bandspread by combining the data with a

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unique wideband code sequence prior to transmission. Subsequent data recovery is by means of a synchronised reception (correlation) with the user's wideband code. Since each user has an individual wideband spreading code, a large number of CDMA signals can be transmitted in the same spectrum, and still be uniquely identified upon reception by correlation with the original spreading code (despreading).

A fundamental property of spread spectrum systems is that of **Processing Gain** associated with the wideband to narrowband conversion process. Any interference present in the wideband channel, including that of other CDMA users, is suppressed by the processing gain of the system. It is this factor alongside that of human **Voice Activity** [5] which allows users to obtain multiple access to the same spectrum, including those in adjacent cells, thereby potentially giving considerable capacity enhancement when compared with narrowband schemes, as illustrated in section 5.0. In addition, it is possible to overlay wideband spread spectrum systems with existing narrowband services, thus further increasing spectrum utilisation. This can be achieved by again exploiting the processing gain which is inherent to this class of system.

### 2.1: RF Carrier Modulation

Numerous modulation techniques can be employed in the RF carrier modulation process with the wideband DS-CDMA signal. The simplest is that of Binary Phase Shift Keying, BPSK, where the phase of the RF carrier is switched between $0^\circ$ and $180^\circ$ in sympathy with the wideband data signal. The spectrum efficiency of a BPSK system can easily be improved, without any degradation in performance, by employing Quadrature Phase Shift Keying, QPSK. Modulation techniques which require coherent demodulation, such as BPSK and QPSK, may prove difficult to implement in the fading signal environment of a land mobile radio channel (see section 2.2). Hence, non-coherent schemes, such as Differential Phase Shift Keying (DPSK), may prove to be attractive.

M-ary modulation of the RF carrier combined with Trellis error correction coding schemes (as described in section 2.4) potentially offer still greater bandwidth efficiency. Minimum Shift Keying, MSK, and various LINEAR modulation formats should also be considered for DS-CDMA networks in light of spectral efficiency claims versus implementation complexity/cost.

### 2.2: Propagation Mechanism of the CDMA Channel

There is seldom a line of sight path between a transmitter and receiver pair when operating in a land mobile radio environment [6]. Reception is usually by means of reflection and diffraction of signal energy from buildings, giving rise to both constructive and destructive interference of the signal as the user moves throughout the service area of the network. This mechanism is illustrated in figure 1, where the Frequency Selective Fading is usually characterised by the **Rayleigh** probability density function (pdf) which describes the **Multipath** nature of the channel, and a **Log-normal** pdf characterizes the path **blockages**, or **shadowing**, due to buildings.

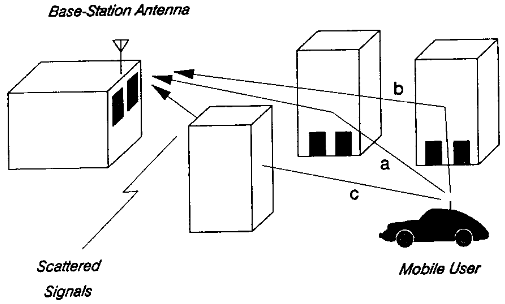

*Figure 1: Signal Propagation Encountered in Land Mobile Radio Systems.*

If sufficient RF bandwidth is employed in a DS-CDMA system, it is possible to resolve the individual multipath signal components at a receiver [7,8]. It is shown in here, that these statistically independent signals can be processed such that the performance of the system is greatly enhanced when compared with that of a single path scheme. However, since RF bandwidth is a scarce and tightly regulated resource, the relationship between resolvable multipath components and bandwidth must be carefully examined.

### 2.3: Internal Diversity Reception

The number of resolvable multipath components, L, is related to the coherence bandwidth, $\Delta f_c$, and also to the bandwidth of the spread spectrum signal, $B_s$. The coherence bandwidth of the channel is the range over which input signals separated by less than $\Delta f_c$, have correlated amplitude and phase responses at the channel output. This quantity is inversely proportional to the total multipath delay spread, $T_m$, of the channel:

$$\Delta f_c = \frac{1}{T_m} \tag{2.1}$$

Similarly, the coherence time is the period over which the impulse response of the channel is correlated in both amplitude and phase. This is inversely proportional to the Doppler spread, $B_d$, of the channel:

$$\Delta t_c = \frac{1}{B_d} \tag{2.2}$$

The time/energy resolution of the wideband correlation process employed in the DS-CDMA system is given by:

$$T_c = 1/B_s \tag{2.3}$$

Where, $T_c$ is more usually referred to as the spreading code chip duration.

The maximum number of resolvable multipath components is thus given by [9]:

$$L \leq \frac{T_m}{T_c} + 1 \qquad (2.4)$$

Hence, a maximum of L statistically independent paths can be resolved directly from the channel, and subsequently utilised in a diversity combining scheme in order to maximise the total wanted signal to noise energy at the input of the demodulator.

The path diversity resolution offered by DS-CDMA is inherent (internal) to the correlation process, with the response shown in figure 2 being typical of the propagation environment given in figure 1. The wanted signal energy extracted from the multipath channel, as illustrated in figure 2, can be exploited in several different combining architectures. Optimum diversity combining performance can be obtained if a Maximal Ratio Combining (MRC) technique is implemented in the form of a RAKE receiver. However, this process requires that the amplitude and phase of every diversity sample is estimated on a continuous basis. This estimation can be performed in the presence of multipath fading if $\Delta t_c / T_s \geq 100$ [10], where $\Delta t_c$ is again the coherence time of the channel, and $T_s$ is the data symbol period. However, if accurate amplitude and phase estimation is not a viable proposition, then equal gain combining (EGC) may yield a better performance. The need to co-phase diversity samples can be avoided if switched diversity combining is used with a corresponding penalty in BER performance.

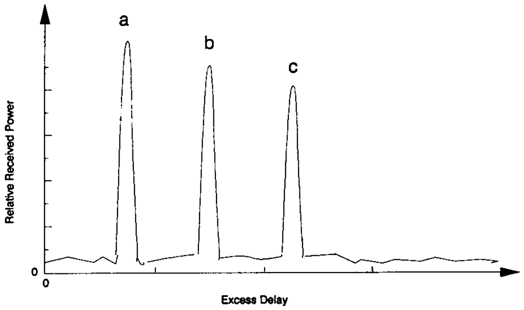

*Figure 2: Channel Sounding Response of Figure 1 Illustrating the Form of Path Diversity.*

In addition to the significant benefits of internal diversity signal processing techniques, site or basestation diversity is also considered to be necessary in these systems. Site, or macroscopic, diversity is discussed further in section 3.0.

## 2.4: Forward Error Correction & Interleaving

Although wideband spread spectrum techniques can be used to combat multipath fading and thus provide a reliable and high quality channel, the underlying spectral efficiency of the system is poor (see figure 6, uncoded for 5 diversity paths). With a relatively small increase in data rate overhead, **Forward Error Correction** (FEC) coding can be employed to further combat the effects of fading and any power control transients (see section 3.0), and thus significantly enhance the spectral efficiency of the system.

FEC coding reduces the BER of the uncoded channel by adding redundancy to the coded data signal. This can be implemented using several different techniques, for example, Block, Convolutional and Trellis codes. To date the application of half rate, constraint length 7, convolutional codes to DS-CDMA systems have received much attention [11]. In these systems optimum performance is obtained by ensuring that the channel errors seen by the FEC scheme are independent (uncorrelated) of each other. Since errors frequently occur in bursts, it is necessary to interleave the FEC data stream in order to obtain uncorrelated errors in consecutive data bits (memory-less channel). Interleaving introduces a time delay into the channel, and for terrestrial voice communication an interleaver depth of not more than 50ms may be considered acceptable [12].

## 2.5: DS-CDMA Transceiver Architecture

The basic form of a CDMA transceiver unit is illustrated in figure 3. The received signal is amplified and downconverted to a suitable frequency where the wideband signal is digitised. Synchronised reception with the user's code is by means of a correlator (matched filter) which also provides diversity path resolution for the signal combiner. The output of the diversity combiner is then demodulated, de-interleaved and FEC decoded before the vocoder extracts the analogue voice signal.

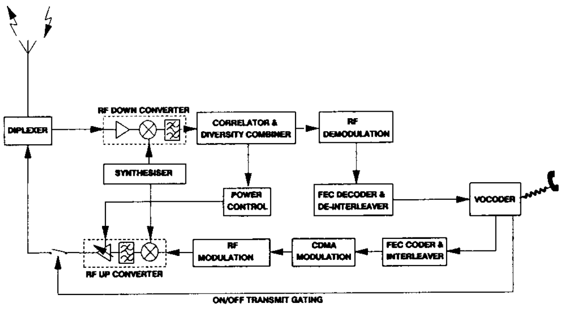

*Figure 3: Basic CDMA Transceiver Unit*

On transmission the speech signal is first vocoded before FEC coding and interleaving. The vocoder also detects the pauses in natural speech flow, and this signal is used to gate the CDMA transmitter on and off. By exploiting the voice activity factor (30% to 35% of time the speaker is quiet [5]), the mutual interference between CDMA users can be significantly reduced, and thus the spectral efficiency of the network increased. The narrowband coded signal is then bandspread with the user's unique spreading code prior to RF modulation, upconversion, RF power amplification, and finally transmission. It should be noted that it is necessary to carefully control the output power of the transmitter as illustrated in figure 3. The need for power control, and a mechanism for its implementation, is discussed further in section 3.0.

## 3.0: DS-CDMA Network Considerations:

Before any cellular network can see operational service, there are many factors concerning its operation, besides those of the underlying modulation and coding techniques, that must be carefully considered. These include call set-up procedures, mobile location register management, handoff mechanism between basestation sites, and power control. Protocols associated with the implementation of handoff and power control will be discussed here, since these are both fundamental to the successful operation of a DS-CDMA cellular network.

### 3.1: Power Control

It is necessary to employ either open or closed loop RF power control in any frequency reuse radio communications network [13]. This is particularly true of narrowband cellular communication networks which operate on a carrier to interference (C/I) limited basis, where the interference originates from users in nearby co-channel cells. In order to provide reliable communications, the power control scheme must ensure that the interference power level in the co-channel cells does not rise above a pre-defined threshold. Also, the power control scheme must ensure that the signals received from all the mobiles are at comparable RF power levels in order to prevent small signal suppression in the cell site receivers.

Power control is mandatory for wideband networks such as DS-CDMA. This class of radio networking potentially offers outstanding performance in terms of frequency reuse, with not only adjacent cells sharing the same frequency allocation, but also the users within each cell utilising the same spectrum. The power control scheme must ensure that the cell site receivers are not captured by a single user who may be in close proximity to the basestation, and thus prevent any distant users from communicating. This effect is more usually referred to as the 'near-far' problem [4]. Further, power control at the cell site may also be desirable in terms of network management.

In order to circumvent the near-far problem in wideband networks, power control with a dynamic range of some 80dB is required, with a resolution (step size) of 1 or 2dB [3]. It has been suggested that a narrow band pilot could be transmitted from the basestation in order to implement a power control scheme at the mobile. In addition, this approach would also aid the mobile receiver in the initial acquisition of the spread spectrum signals. However, when this approach is employed in a mobile radio channel, which has log-normal Rayleigh fading characteristics, it is found that the narrowband pilot is uncorrelated with the wideband channel for which it is required to provide an accurate power level reference. The use of a wideband pilot, or control channel, would serve to overcome this problem.

The dynamic response of the power control loop is also important, since when blockage or shadowing occurs the RF power must be increased quickly, if the error rate bound is not to be exceeded. In contrast, when a user moves away from the radio path obstruction (blockage), his power must be reduced quickly, otherwise all other users being served by the basestation will be suppressed by his strong wideband signal.

### 3.2: Power Control & Handoff Protocols

#### 3.2.1: Reverse Link (M → B)

The control problem can be explained as follows by considering the scenario of events depicted in figure 4. Initially assume that mobile M1 is controlled by basestation B1, and since M1 is shadowed and also at some considerable distance from B1, it will be operating at maximum RF power. Also, a similar scenario exists for M3 and B2, with M3 operating at maximum power level. As mobile M3 moves southwards a short distance, it gains a line of sight path with B1, and since M1 and M3 operate at similar frequencies (shared spectrum), B1 would receive M3 at several orders of magnitude greater than M1. Thus M3 would suppress reception of M1, and **all** other mobiles currently served by B1. The solution to this problem is the immediate handoff of M3 to the control of B1. As M3 continues to moves further south, control is again returned to B2, since this path offers the minimum attenuation to the transmitted signal. This application of **Switched Cell Diversity** would have to apply to the union of the 7 adjoining cells in the CDMA network.

With mobile M1 moving southwards, a line of sight path will be obtained with its controlling basestation (B1), with blockage of path to B2. Since M1 was previously operating at full power due to shadowing of path with B1, M1 must now reduce power if communications is to be maintained with all users served by B1 (small signal suppression). In conventional cellular schemes, the RF power level is usually ramped down in order to obtain a specific operating level, however this process takes a finite time depending upon the required

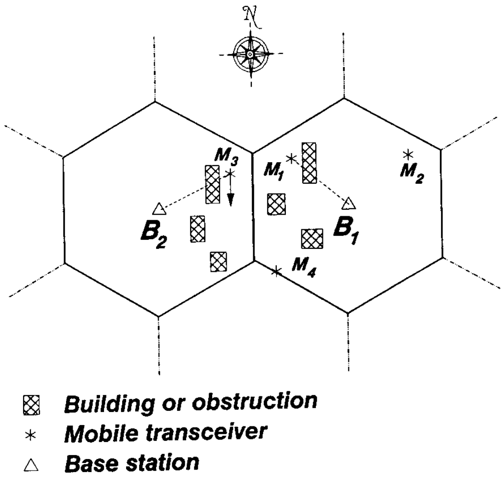

*Figure 4: Requirement for Dynamic Power Control*

dynamic range. An instantaneous measurement and power adjustment scheme may initially appear to be a suitable alternative, however power control is employed in order to mitigate the long-term effects of shadowing, and **not** short-term multipath fades. Further, the time constant of the power control loop should be such that instability does not result.

If a similar approach is adopted for a DS-CDMA system, K - 1 users served by the basestation will be blocked during the ramp down period of the power control transient. Although coding and interleaving can be employed to mitigate this effect to some extent, the depth of interleaving (processing delay) cannot be increased without limit in order to circumvent the loss of the channels when several users enter this process in a sequential manner. In order to employ an acceptable interleaver depth (<50ms), it is proposed here that the power ramp down scheme is replaced with a **'set power to zero and ramp up'** power control algorithm. Using this approach, the coder and interleaver have only to compensate for very short power transient spikes of other users as they become un-shadowed, and the self induced loss of channel during the power ramp-up period.

### 3.2.2: Forward Link (B ⟶ M)

When both the forward and reverse links are considered together from a power control aspect, it is found that the 'near-far' problem cannot be overcome unless different frequency bands are employed for the two links. Further, it is assumed that sufficient frequency separation exists (45MHz is typical of US cellular systems), such that the necessary isolation can be obtained from a conventional diplexer filter as shown in figure 3.

The transmit power level of the cell site is not tailored to meet the needs of individual users, it is set by ensuring that a channel can be obtained within the service area of the network from at least one basestation. That is, the basestation power is sufficient to overcome shadowing (see mobile M4 which is currently blocked from both B1 and B2). As far as handoff is concerned, the scenario is identical to that described above since shadowing is a long term effect, and the log-normal fading characteristics of the forward and reverse channels are very similar.

The service area of a basestation site is governed by output power, provided that the number of simultaneous users within that service area is less than a pre-defined limit, given by the $E_b/N_o$ ratio required to maintain a specific vocoder error rate (see section 4.0). Thus, additional cell sites can be introduced into the network to provide more channels by simply controlling the transmit power. Unlike narrowband networks, no expensive frequency planning is necessary in order to provide more capacity, on either a temporary, or permanent, basis.

## 4.0: Performance Analysis

In order to compare DS-CDMA with other multiple access schemes currently favoured for future generation cellular networks, it is first necessary to evaluate the spectral efficiency of the system. In the analysis presented below, the bandwidth efficiency is calculated as a function of the number of diversity branches employed, diversity combining/selection technique, RF modulation scheme, FEC coder type, and background noise level (thermal and other DS-CDMA users). Since these calculations involve the computation of complicated double integrals, the solutions have been obtained by numerical methods.

### 4.1: Assumptions

In the analysis presented here, the following assumptions have been made regarding the implementation of the DS-CDMA cellular network:

(a): Ideal power control.
(b): CDMA interference modelled as Gaussian noise, under the assumption that the number of simultaneous asynchronous users is sufficiently large.
(c): Sufficient bandwidth such that uncorrelated paths exist for a given diversity order.
(d): Perfect CDMA code synchronization.
(e): Voice activity detection, $G_{VA} = 2.8$ (35% active)
(f): Ideal interleaving of FEC symbols.
(g): Soft decision decoding.
(h): Frequency reuse efficiency, $L_{FR} = 0.67$ [3].
(i): No antenna sectorization.
(j): Signal to thermal noise level, $E_b/N_o = 10\text{dB}$.
(k): Vocoder symbol period, $T_s = 10^{-4}$s.

## 4.2: DS-CDMA Bandwidth Efficiency Model

The model which has been developed at the CCR allows the bandwidth efficiency of both the mobile to base path (reverse link), and the base to mobile path (forward link), to be evaluated for various DS-CDMA transceiver architectures as illustrated in table 1.

| Parameter | Options |
|---|---|
| Channel Model | Log-normal Rayleigh or Rician |
| No. of Resolvable Diversity paths | ≥ 1 |
| Internal Diversity Architecture | Maximal Ratio<br>Equal Gain<br>Switched |
| RF Modulation | BPSK, QPSK, M-ary |
| FEC Coding | Block<br>Convolutional<br>Trellis |

*Table 1: Model Run-Time Options*

The evaluation of spectral efficiency for a given DS-CDMA implementation involves three basic steps. The first is that of the calculation of the **coding channel cut-off rate**, $R_o$, for the specified radio channel and internal diversity combining scheme. This gives the highest practical data rate in bits/symbol, where $R_o$ is expressed by:

$$R_0 = \log_2 M - \log_2\{1+(M-1)D\} \qquad (4.1)$$

Here, M is the number of different symbols employed in the RF modulation scheme, with both D and $R_o$ independent of type of FEC coding used. The parameter D is dependent on the ratio of bit energy ($E_b$) to the spectral noise density ($N_I$) arising from other CDMA users, and also on the form of internal diversity reception employed in the receiver. The computation of D was performed using the Chernoff Bound [9]. For example, in the case of maximal ratio combining and a log-normal Rayleigh fading channel, D is given by:

$$D = \left[ E\left\{ \exp\left( \frac{-T_s A^2}{2N_I} \right) \right\} \right]^L \qquad (4.2)$$

Where, L is the order of diversity, and E{ } is the expected value over the faded signal amplitude, A.

The coding channel cut-off rate as a function of $E_b/N_I$ for L branch maximal ratio combining (L= 1,2,5,10 & 20) is given in figure 5 for QPSK (M = 4) modulation, and a log-normal Rayleigh fading channel (shadowing, $\sigma$ = 8dB). Here, $E_b$ is the average energy over the fading channel.

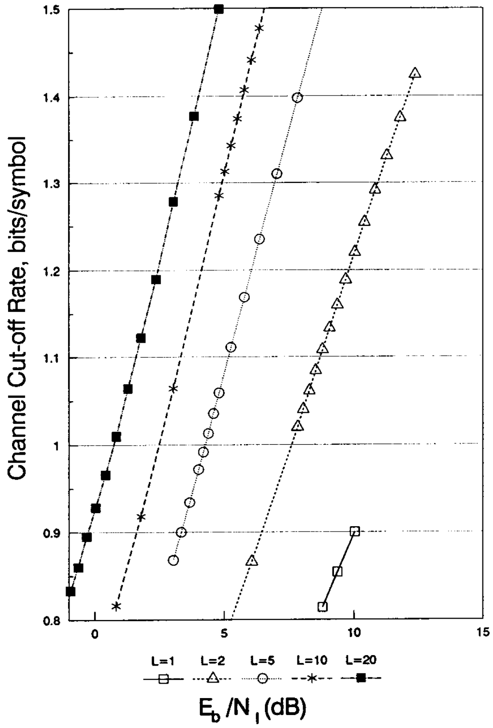

*Figure 5: Coding Channel Cut-off Rate for Maximal Ratio Combining in a Log-Normal Rayleigh Channel ($\sigma$ = 8dB).*

From the parameter D, the BER bound ($P_b$) can be evaluated by means of the Union bound, using the transfer function of the FEC code employed. For the example FEC code used in the bandwidth efficiency calculation given below, $P_b$ is obtained from:

$$P_b \leq \frac{1}{2}\left(36D^{10}+211D^{12}+1404D^{14}+11633D^{16}+\ldots\right) \qquad (4.3)$$

which corresponds to a half-rate (R= 1/2) convolutional code of constraint length 7. Figure 6 shows the BER bound versus $E_b/N_I$ for the FEC code given by equation (4.3) as a function of diversity order for a maximal ratio combining scheme. It can be seen that for a constant BER performance, the required $E_b/N_I$ can be significantly reduced if the diversity order is increased by an appropriate degree.

From the BER bound the $E_b/N_I$ ratio can be obtained for a specific vocoder error rate, and the resulting bandwidth efficiency (assuming random spreading codes), is calculated from:

$$\eta \approx 3R\log_2(M)G_{VA}L_{FR}\left(\left[\frac{N_I}{E_b}\right]_{REQ} - \frac{N_0}{E_b}\right) \qquad (4.4)$$

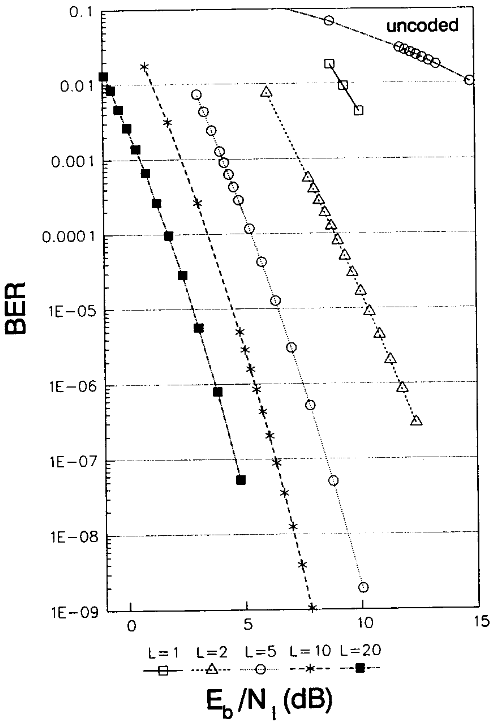

*Figure 6: BER Bound for coding channel given in figure 5 for a convolutional FEC code (R=1/2, constraint length=7)*

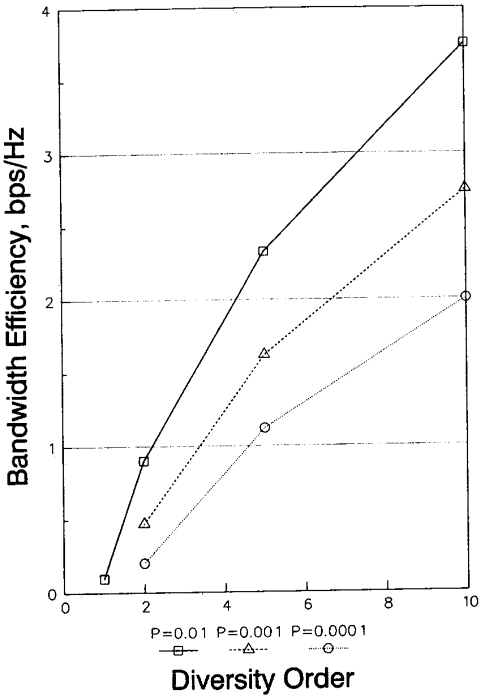

*Figure 7: Bandwidth Efficiency for Maximal Ratio Combining versus Diversity Order for various Vocoder error rates*

This is illustrated in figure 7 for the operational parameters considered above. From the results given it can be seen that by increasing the order of internal diversity, there is a corresponding increase in the bandwidth efficiency of the system. This effect is particularly pronounced when considering the performance of systems which employ low order diversity schemes. Further, the trade-off in bandwidth efficiency resulting from variations in the diversity order should be carefully considered in light of the required implementation complexity and power consumption.

## 5.0: Conclusions

The bandwidth efficiency of a CDMA cellular network is inversely proportional to the Eb/Ni ratio required to maintain the vocoder bit error rate specification. Unlike narrowband networks where capacity is limited by bandwidth restrictions, CDMA schemes are limited by mutual interference. It is shown that by employing an internal diversity combining architecture, a much lower Eb/Ni level can be tolerated for an identical vocoder performance, thereby increasing the spectral efficiency of the network. However, the use of internal diversity necessitates that the RF bandwidth is sufficient to support the required diversity path resolution.

Using the results presented in figure 7, the capacity (users/MHz/cell) of a hypothetical DS-CDMA system can be compared with that of existing and proposed narrowband cellular schemes, assuming where appropriate a vocoder error rate of $<10^{-3}$. The capacity comparisons given in table 2 assume that no antenna sectorization has been employed, since this yields approximately equal gains in capacity for all the different systems considered.

It can be seen that DS-CDMA potentially offers significant gains in system capacity when compared with narrowband techniques, thus substantiating some of the claims made by the proponents of spread spectrum techniques [1,2]. However, it also should be noted that there is a dramatic increase in channel capacity for DS-CDMA systems, if five path internal diversity is employed rather than a two path scheme.

In the results presented for the reverse link bandwidth efficiency, it is assumed that ideal power control exists in order to circumvent the 'near-far' problem associated with DS-CDMA systems.

| System | AMPS | TACS | GSM | D-AMPS | CCR CDMA | |
|---|---|---|---|---|---|---|
| | | | | | L=2 | L=5 |
| Access Method | FDMA | FDMA | FDMA<br>TDMA | FDMA<br>TDMA | CDMA | CDMA |
| Vocoder Rate (Kbps) | --- | --- | 13.0 | 6.4 | 10 | 10 |
| Channel Bandwidth | 30 KHz | 25 KHz | 200 KHz | 30 KHz | 2 MHz | 2 MHz |
| Frequency Re-use Pattern Size | 7 | 7 | 4 | 7 | 1 | 1 |
| Capacity (channels/ MHz/cell) | 5 | 6 | 10 | 14 | 48 | 154 |

*Table 2: Channel Capacity Comparison*

A power control and hand-off protocol based on rapid **switched cell diversity**, and a novel **'set power to zero and ramp-up'** algorithm has been proposed as a possible implementation of this assumption.

Finally, work to be undertaken at Bristol in the near future will address the following areas: capacity evaluation of differing forward and reverse links, use of non-coherent demodulation, detailed study of FEC coding requirements (including that of burst error correcting cyclic or convolutional codes [14]), selection of spreading codes, implementation of correlator/diversity combiner, and an evaluation of **Frequency Hopping** techniques. Using the computer model described in this paper, the trade-offs between various alternative systems implementations can thus be assessed.

## 6.0 Acknowledgements

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