TRANSMITTER DIVERSITY IN CDMA SYSTEMS

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Abstract

In wireless communication, diversity techniques are widely used in order to improve the performance of data transmission over fading radio channels. Transmitter diversity, in particular, is gaining a lot of attention lately in the wireless community. In his paper [1], Alamouti showed that a simple transmitter diversity technique could, by taking advantage of the time dimension (space-time coding), provide similar performance to that of receiver diversity with maximum ratio combining (MRC) scheme.

An important limiting factor in modern radio communications is the simultaneous use of the radio spectrum by a large number of users. Due to this, radio links experience interference from other radio transmitters in the system. In many cases, this interference is the phenomenon which makes reliable transmission difficult in wireless systems. In this work, we investigate the capacity of a Code Division Multiple Access (CDMA) system with the above-mentioned transmitter diversity technique and assess the interaction between diversity gain and experienced interference.

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Chapter 1

Introduction

1.1 Background

Diversity methods are important in wireless communications as they improve the system performance without the need for extra fade margins. One of the diversity methods and the one that we will study is space diversity. The most commonly used space diversity method is receiver diversity, where several uncorrelated replicas of the signals are combined at the receiver in order to improve the signal reconstruction. Diversity can also be achieved through transmitter diversity, that is by using several antennas to transmit the signal. These antennas are placed sufficiently far apart to get uncorrelated signals on the receiver end. Transmitter diversity is not commonly used in practice yet. Actually, the drawback of transmitter diversity is mostly the difficulty in separating, at the receiver, the signals from the different transmitting antennas. By taking advantage of the time dimension, this problem can be solved: a simple two-branch transmit diversity (STD) scheme, referred to as space-time multiplexing, has been presented in [1]. This provides the same diversity order as MRC with one transmit antenna and two receive antennas, without increasing the computation complexity.

Such a technique, which is based on orthogonal design, is optimum when there is no interference at all. In the presence of interference, both the useful signal and the interference can add coherently at the receiver when applying Alamouti's combining scheme. This means that the diversity technique potentially increases the experienced interference compared to a single antenna systems (SAS).

1.2 Task

Based on Alamouti's paper, our main task is to examine and measure how this STD technique performs in a realistic CDMA system, where the limiting factor on the system performance is the interference created by other users. By running simulations both on SAS and STD versions of our CDMA system, the system capacity for a given bit error rate (BER) and availability can be calculated and compared.

1.3 Report outline

The organization of the report is as follows: in Chapter 2, the CDMA system model we make use of is presented. In Chapter 3 we present the implementation of our simulation program. Results derived from our simulations are exposed and compared to that of SAS in Chapter 4. In Chapter 5 some conclusions and possible future work are commented.

Chapter 2

System model

Our model consists a group of mobile terminals in a cellular network which transmit data to their respective base stations. The mobiles transmit either with one antenna (SAS) or with two antennas (STD) which are at a sufficient distance so that the two copies of the information to be transmitted are affected by independent channels. The data transmitted by the users is decoded at the base station, giving us bit error rate (BER) measurements which will allow us to assess the quality of the links.

We focus on a snapshot of the uplink situation, so user behavior, i.e. traffic intensity and call duration, is not subject of our study. To investigate the uplink is more interesting because near-far effect is stronger in that link, although a power control algorithm is implemented (Constant Received Power) to combat this problem.

Seeing that our aim is to evaluate how STD reacts in the presence of interference, we do not consider any channel encoding techniques such as FEC or ARQ to protect data against errors, that is to say, no other digital signal processing than the Alamouti's implementation is used.

2.1 Service area, user distribution

Users are uniformly distributed over the service area which is composed of 1, 7 or 9 hexagonal cells. Users transmit with no mobility, handovers, arrivals or departures because we are only interested in how the system behaves in a steady state, not how the system evolves over time. All users use the entire bandwidth simultaneously since we are dealing with a CDMA system.

2.2 Transmission

2.2.1 Modulation and DS-CDMA spreading

Each user's data sequence is first modulated using BPSK modulation. Each user within a cell is assigned a unique signature waveform $c(t)$, called spreading or pseudo-noise

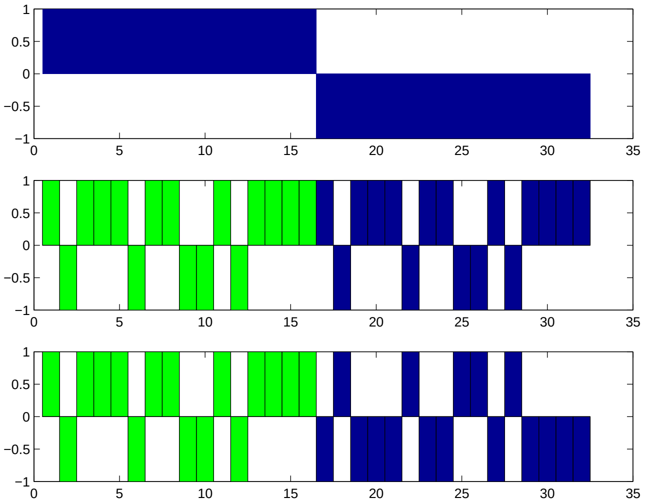

Figure 2.1: user data (2 bits), PN sequence and spread signal

(PN) code, which is then used to spread the BPSK-modulated signal using direct-sequence CDMA (DS-CDMA).

Our CDMA system has a spreading factor (or processing gain) of $N = 64$, so as to match that of IS-95. The system is direct-sequence, so the spreading is a simple multiplication of the BPSK-modulated signal by the PN code mapped to bipolar format - that is BPSK modulation with a rectangular pulse. After mapping the PN code takes the form

$$c(t) = \sum_{k=0}^{N-1} c_k p(t - kT_c), \qquad 0 \leq t < T_b = NT_c$$

with $c_k = \pm 1$ and $p(t)$ is a rectangular pulse of duration T_c and unit amplitude. The relation between user data, PN sequence and spread signal is illustrated in Figure 2.1.

The codes are Walsh and Hadamard sequences, so they are orthogonal if the users transmit in a synchronous fashion, but we will see that when users within a given cell are not synchronised, the loss of orthogonality between the users causes intra-cell interference.

2.2.2 Single antenna system

At the n^{th} symbol interval, the equivalent low-pass of the transmitted signal is given by

$$s(t) = m(t)c(t), \qquad nT_b \leq t < (n+1)T_b$$

where $m(t) = \sqrt{\frac{E_b}{T_b}} b_n$ is the BPSK baseband signal with $b_n = \pm 1$.

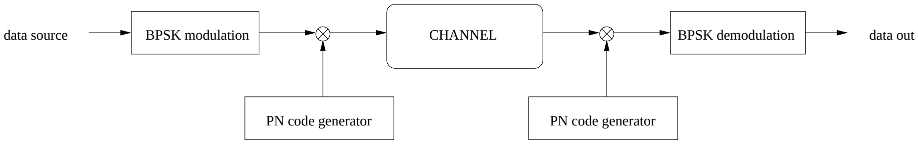

Figure 2.2: DS-CDMA chain without Alamouti code (SAS)

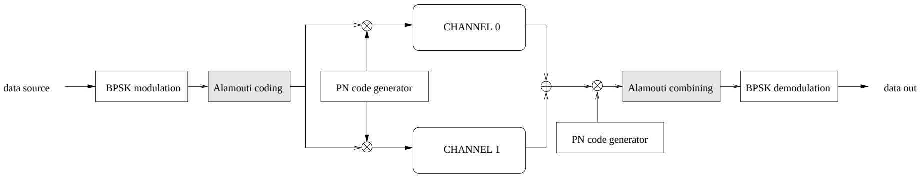

Figure 2.3: DS-CDMA chain with Alamouti code (STD)

2.2.3 Transmitter diversity technique

The Alamouti coding scheme uses two transmit antennas at each mobile station and one receive antenna at the base station. The processing on the transmitter side is done between the modulation and the spreading stage. At the n^{th} symbol interval, signals $s_1(t)$ and $s_2(t)$ are simultaneously transmitted respectively by antennas 1 and 2, and $-s_2^\star(t)$ and $s_1^\star(t)$ are transmitted during the next symbol interval. In other words, the equivalent low-pass of the transmitted signals over two symbol intervals are

$$\begin{array}{lcr} s_1(t) \text{ at time } t & \text{then} & -s_2^\star(t) \text{ at time } t+T_b \\ s_2(t) \text{ at time } t & \text{then} & s_1^\star(t) \text{ at time } t+T_b. \end{array}$$

Note that this method does not alter the bandwidth efficiency of the system, it only multiplexes modulated symbols in space and time (space-time coding).

2.2.4 Power control

In the absence of power control the capacity of CDMA systems is very low. CDMA cellular networks require accurate power management to function, especially in the uplink, due to the near-far effect. Power control ensures that each user transmits enough energy to properly convey his information without creating excessive interference for the other users. Power control extends battery life as well, by using minimum of transmitter power to achieve the required transmission quality.

For the sake of simplicity, we employ a Constant Received Power (CRP) algorithm. CRP is a power control algorithm which assigns different power to every user within the cell such that the base station receives the same level of power from every user. CRP is also restricted by the maximum transmitted power of the users.

2.3 Radio channel features

While travelling over the communication channel, the signals are corrupted by several phenomena.

2.3.1 Fast fading

The fast fading is due to multi-path propagation. The response of the channel to an input symbol in general affects several successive output symbols, i.e. the details of the transmitted signal. We say also that inter-symbol interference is experienced.

The radio channel is modelled as a Rayleigh fading channel with impulse response $h(\tau;t) = h(t)\delta(\tau)$ where $h(t)$ is a complex multiplicative distortion modelled as a Gaussian process having zero-mean and power spectral density $2\sigma^2 = 1$. Note that the variance of this distortion is unity so that the fading channel does not amplify the system.

Assuming that the channel is slowly varying and can be considered constant across (at least) two symbol intervals, the multiplicative distortion experienced during symbols n and $n+1$ from antenna i can be written as

$$h_i(t) = h_{i,n} \quad nT_b \leq t < (n+2)T_b \quad i = \{1,2\}.$$

2.3.2 Slow fading

Slow fading is due to shadowing of the transmitted signals by large obstructions such as hills or buildings in urban areas. Slow fading affects the average power of transmitted signals and is assumed to be constant during all the time that the transmission takes place. The received power can then be approximated according to the formula

$$P_r = G\frac{cP_t}{r^\alpha}$$

where G represents log-normal shadowing with zero mean and standard deviation σ_s, c is a gain constant determined by the carrier frequency and antenna height, r is the distance between the active user and the BS he is assigned to, α is the power of distance dependent path loss.

2.3.3 Interference

In cellular systems two kinds of interference exist. The first one comes from other mobile stations within the cell (in the uplink case) also known as intra-cell interference. The second one comes from all the mobile stations in other cells and usually represents about 60% of the total interference (inter-cell interference). This total interference limits the capacity and performance of CDMA because as the number of users increases so too does the interference, thereby limiting the number of users that are allowed in a cell to guarantee a certain transmission quality.

An important factor that influences the interference is the path loss, which is controlled by the factor α. The path loss and also the shadow fading can make an interferer seem inexistent if the distance is large enough. As we increase α the path loss factor becomes more important and the effect of the interferers (especially external interferers) decreases.

2.3.4 Noise

CDMA systems are usually considered as interference limited systems, meaning the noise term can be neglected compared to interference. The additive noise should be taken into account when considering a system with very few users as it will impose a lower bound on the bit error rate, but as we are interested in the system capacity, we consider scenarios with a large number of users and the noise is not as important as the interference caused by the other users in the system.

2.4 Reception

2.4.1 Single antenna system

We focus on user j during n^{th} symbol interval. The received signal at the base station (BS) can be written as follows

$$r(t) = h_{j,n}s_j(t) + i(t)$$

where $h_{j,n}$is the complex distortion constant over two symbols at least and $i(t) = \sum_{k\neq j} h_{k,n}s_k(t)$ is the total interference. Note that when the users' signals arrive unsynchronised at the base station, we have to take the delays of all incoming signals into account. In that case, the received signal is also given by

$$r(t) = h_{j,n}s_j(t) + \sum_{k\neq j} h_{k,n}s_k(t-\tau_k)$$

where $\tau_k \leq T_b/2$ is the time delay of user k.

After despreading, the useful signal is restored to its original form $m_j(t)$ and the interference is spread over the total bandwidth. At the output of the BPSK correlator, the decision variable $r_{j,n}$ used to detect user j's information bit $b_{j,n}$ is expressed as

$$r_{j,n} = b_{j,n}h_{j,n}\sqrt{E_b} + i_n$$

where i_n is an interference random variable which can be expressed as

$$i_n = \int_{nT_b}^{(n+1)T_b} i(t)c_j(t)dt = \sum_{k\neq j} \rho_{kj}b_{k,n}h_{k,n}\sqrt{E_b}$$

where ρ_{kj} is the correlation coefficient between the PN codes $c_k(t)$ and $c_j(t)$.

2.4.2 Receiver combining method

Here again, we focus on user j during n^{th} symbol interval. Under synchronous operation, the received signals for two consecutive symbols of one given user j can be expressed as

$$\begin{aligned} r(t) &= h_{1,n}s_{1,j}(t) + h_{2,n}s_{2,j}(t) + i(t) \\ r(t+T_b) &= -h_{1,n}s^{\star}_{2,j}(t) + h_{2,n}s^{\star}_{1,j}(t) + i(t+T_b) \end{aligned}$$

where $i(t) = \sum_{k \neq j} h_{k,n}\left(s_{1,k}(t) + s_{2,k}(t)\right)$.

Both signals transmitted by user k during the n^{th} symbol interval are assumed to suffer the same channel distortion $h_{k,n}$. Therefore, $i(t)$ represents the total interference experienced at the BS to which user j is assigned. Despreading by $c_j(t)$, the output of the demodulator (correlator) can be also written

$$\begin{aligned} r_{j,n} &= h_{1,n}b_{j,n}\sqrt{E_b} + h_{2,n}b_{j,n+1}\sqrt{E_b} + i_n \\ r_{j,n+1} &= -h_{1,n}b_{j,n+1}\sqrt{E_b} + h_{2,n}b_{j,n}\sqrt{E_b} + i_{n+1} \end{aligned}$$

where

$$i_n = \int_{nT_b}^{(n+1)T_b} i(t)c_j(t)dt = \sum_{k \neq j} \rho_{jk}h_{k,n}\left(b_{k,n} + b_{k,n+1}\right)\sqrt{E_b}$$

is an interference random variable with variance σ_I^2.

Based on the samples $r_{j,n}$ and $r_{j,n+1}$, Alamouti's combiner builds the two signals $v_{j,n}$ and $v_{j,n+1}$ that are then sent to the detector

$$\begin{aligned} v_{j,n} &= h^{\star}_{1,n}r_{j,n} + h_{2,n}r^{\star}_{j,n+1} \\ v_{j,n+1} &= h^{\star}_{2,n}r_{j,n} - h_{1,n}r^{\star}_{j,n+1}. \end{aligned}$$

It should be noted that as the object of this paper is not channel estimation, perfect channel knowledge is assumed. From the previous expressions of $r_{j,n}$ and $r_{j,n+1}$we can rewrite the decision variables $v_{j,n}$ and $v_{j,n+1}$ as

$$\begin{aligned} v_{j,n} &= \left(|h_{1,n}|^2 + |h_{2,n}|^2\right) b_{j,n}\sqrt{E_b} + J_n \\ v_{j,n+1} &= \left(|h_{1,n}|^2 + |h_{2,n}|^2\right) b_{j,n+1}\sqrt{E_b} + J_{n+1} \end{aligned}$$

where

$$J_n = h^{\star}_{1,n}i_n + h_{2,n}i^{\star}_{n+1} = \sum_{k \neq j} \rho_{jk}\sqrt{E_b}\left(b_{k,n} + b_{k,n+1}\right)\left(h^{\star}_{1,n}h_{k,n} + h_{2,n}h^{\star}_{k,n}\right)$$

is an interference random variable with variance $\left(|h_{1,n}|^2 + |h_{2,n}|^2\right)\sigma_I^2$.

The signals $v_{j,n}$ and $v_{j,n+1}$ are similar to that of a two branch receiver diversity system with maximum ratio combining (MRC) where the combiner compensates for the phase and amplitude of the fading channel coefficients. Due to the power split between the STD's two transmit antennas, for a fair comparison we need to consider a power 3 dB lower when examining STD compared to a two receive antenna diversity with MRC.

2.4.3 SIR and capacity

2.4.3.1 General case

Considering the useful signal from terminal j, the signal-to-interference ratio Γ_i at the base station i is given by

$$\Gamma_i = \frac{W_c}{R_s} \frac{G_{ji}F_{ji}P_j}{(1-\chi)\left[\sum_{k=1,k\neq j}^{M} G_{ki}F_{ki}P_k + \sum_{n=1}^{L} G_{ni}F_{ni}P_n\right]} = \frac{W_c}{R_s} \frac{G_{ji}F_{ji}P_j}{I_{intra}+I_{inter}}$$

where:

- M is the number of active users within the cell corresponding to base station i,
- L is the number of active users in the neighbouring cells,
- $W_c \approx \frac{1}{T_c}$ is the system bandwidth,
- $R_s \approx \frac{1}{T_b}$ is the information data rate,
- G_{ji} represents the log-normal shadowing and F_{ji} the fast fading,
- χ is the orthogonality factor between users.

$\chi = 1$ means that users' signals are perfectly orthogonal to each other and then do not interfere. In the uplink we can assume that we lose orthogonality due to the different transmission delays so we set $\chi = 0$.

Under the same assumptions as in [5], with perfect Constant Received Power (CRP) we get

$$\Gamma_i \approx \frac{W_c}{R_s} \frac{1}{(M-1)+L} = \frac{W_c}{R_S F(M-1)}$$

where F is the frequency reuse factor as $F = \frac{\text{total interference power}}{\text{own-cell interference power}} \approx 1.6$. The inter-cell interference is about 60% of the intra-cell interference (common assumption). If an SIR threshold of γ_t is required to achieve good signal quality the capacity of the multi-cell DS-CDMA systems can be approximated as

$$M \approx 1 + \frac{W_c}{FR_s}\frac{1}{\gamma_t}$$

2.4.3.2 Capacity calculation

For the single antenna system (SAS), using Figure 2.4, we deduce $\gamma_t = 11$ dB at $BER = 2\%$. This gives us a capacity of $M = 4.2$ users/cell.

For two receive antenna diversity with MRC, for a $BER = 2\%$ we need an SIR threshold of 6 dB. To take into account the power split, in the STD case we need a γ_t 3 dB higher than that of MRC. Therefore, $\gamma_t = 9$ dB and so the capacity for STD is $M = 6.1$ users/cell.

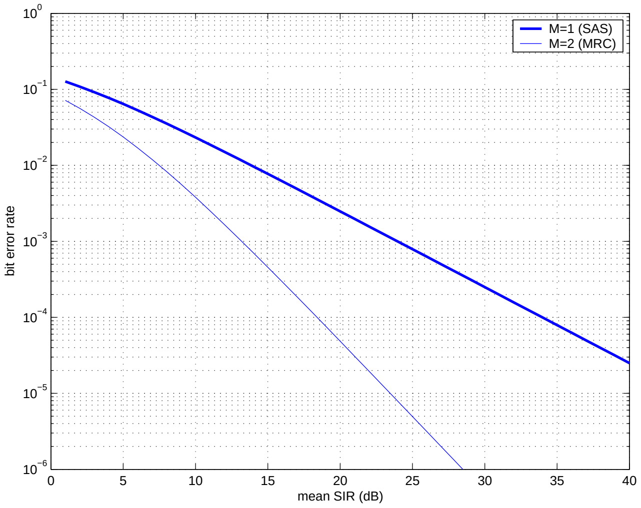

Figure 2.4: BER as a function of the SIR threshold

Chapter 3

Implementation

Our simulation system is implemented as a set of MATLAB functions, some of which make use of the RUNE package developed by Magnus Almgren and Olav Queseth [2]. A single run of the simulator is achieved through the use of the *cdma_test* function which creates a user distribution and allocates users to base stations (BS), generates the signals transmitted by all the users, sends these signals through the radio channel, decodes the signals received at the base stations and finally compares the decoded data with the transmitted data. Two piloting functions for large simulation runs have also been included.

Please note that all the functions which are referred in the paragraphs that follow have been documented and have a help section explaining their usage and their parameters.

3.1 User distribution, power control

To start off with, we create the simulation area using functions from the RUNE package. This results in an area paved with an adjustable number of hexagonal cells, with one base station in the center of each of these cells. The configurations used were either a single cell to study intra-cell interference or 7 or 9 cells.

Users are then randomly and evenly distributed over this area and allocated to their nearest base station. The power control chosen is a simple constant received power (CRP) scheme : the mobiles' transmit power is set in such a fashion that it compensates the deterministic path loss and slow (shadow) fading to the BS it is connected to.

3.2 Generation of the user signals

The next step in our simulation is to generate the signals to be transmitted by each mobile. A random data sequence of length *par.nbits* is created and sent through the BPSK modulator, then through the CDMA spreader. Each user's transmission starts at a random time so that the spreading codes are no longer truly orthogonal. The function *cdma_transmit* returns a matrix containing the samples of each user's transmission.

The number of samples per data bit - the length of the pulse used for modulation - can be adjusted by setting *par.tb*. The number of samples per chip is controlled by the *par.tc*. In our simulations we used a plain rectangular pulse shape and as there is no processing done below the chip level we set one sample per chip (*par.tc=1*).

3.3 Channel

After generating the user signals, we do the processing which corresponds to the communication channel. A gain matrix is calculated, taking into account deterministic path loss with an exponent $\alpha = 4$ to simulate an urban environment and log-normal shadow fading with $\sigma_s = 6$. This gain matrix remains constant over the duration of the transmission. On top of this slow fading, the signals from each one of the user's antennas experience independent Raleigh fading. As in [1], the channel's characteristics are considered to be constant over two consecutive symbol intervals.

3.4 Reception by the base stations

The signal received at each base station is computed from the user signals, their transmit power and the channel effects. Each user's transmission is despread and demodulated by its matching base station. If the Alamouti transmitter diversity technique is enabled, additional processing takes place between the despreading and the demodulation. We have assumed perfect channel knowledge, which in practical terms means that the channel coefficients are given to the Alamouti combining function. The received data is then compared to the transmitted data, which gives us a bit error rate (BER).

3.5 Batch simulations

In order to standardise our simulation conditions and be able to run simulations simultaneously on several workstations, we wrote two functions (*cdma_batch_ber* and *cdma_batch_outage*) which perform the measurements detailed in 4.1.1 and save the results to a file. The plots found in this report can be generated from a set of results using the *cdma_plot_ber* and *cdma_plot_outage* functions.

Chapter 4

Results

4.1 About the experiments

We developed a DS-CDMA system at link level over MATLAB. In the simulation environment we work with the signal and the transmitted bits and hence decided to use the bit error as the criterion for evaluating the system performance.

4.1.1 Types of measurements

When running our experiments, we performed two types of measurements. The first is a measurement of the average bit error rate as a function of the number of users in the system. For each number of users we ran 40 iterations during which the users transmit 400 bits of data each to obtain statistically correct results and extracted the average bit error rate. This allowed us to see how the Alamouti code performed on average and gave us a rough estimate of the capacity to expect. Plots corresponding to these measurements are found in Figures 4.1, 4.3 and 4.4.

The second type of measurement is aimed at evaluating the capacity of our system. Here for each of a few selected numbers of users per cell, we perform enough iterations (each user transmits 1000 data bits at each iteration) to get the BER measurements of 1000 links and plot the cumulative distribution function (CDF) of the BER. These plots are found in Figures 4.2, 4.5 and 4.6. If we now fix a BER threshold of 2% as the requirement for a link to be considered supported and say we want 85% availability, we can read the system capacity from the CDF plot. This allows us to compute the capacity of both systems, the standard CDMA and the one with Alamouti technique.

4.1.2 Scenarios studied

Both systems were studied in several scenarios. First we examined both single cell and multiple cells scenarios in order to see how our systems are affected by intra-cell interference only (single cell case) and by both intra-cell and inter-cell interference (multiple cells case). We also examined both the case where the users' signals arrive synchronised and when they arrive non-synchronised, allowing us to suppress or enable intra-cell interference.

4.1.3 Parameters

parameter	description	value
par.alamouti	set the alamouti code or not	0 or 1
par.cellradius	radius of the cell(s)	1000
par.sigma	log-normal fading	6
par.alpha	exponent of the distance in path loss calculation	4
par.ups	maximum users per cell (spreading code length)	64
par.tc	chip duration (in samples)	1
par.tb	data bit duration (in samples)	par.tc * par.ups
par.nusers	number of users	1..108
par.ncells	number of cells	1,7,9
par.data_len	number of transmitted data bits per user	400, 1000

4.2 Single cell

In this scenario, we consider only one cell so as to assess the influence of intra-cell interference - that is interference due to other users of the same cell.

4.2.1 Synchronous case

If the users transmit in such a way that their signals arrive synchronised at the base station, the signals from the different users are orthogonal and we do not experience any interference. As we do not consider any additive noise, we get the expected result which is that even when all the spreading codes can be used the bit error rate is zero. The resulting cell capacity is therefore 64 users. This result remains the same with or without the Alamouti code, as expected. The main point of this experiment was to validate our transmission / reception chain.

4.2.2 Asynchronous case

If we now allow the users to start transmitting at a random time between instant zero and the duration of one data bit (i.e. one period of the spreading sequence), we break the orthogonality of the PN codes and we experience intra-cell interference.

4.2.2.1 Average BER

In Figure 4.1 we can see that the use of the Alamouti transmit diversity technique approximately divides the average BER by two. If for example we look at the number of users which can be allowed into the system for an average BER of 2%, we see that with the diversity technique we can have 15 users where as in the standard CDMA system we can have only 8 users. It should be noted that this is not the actual cell

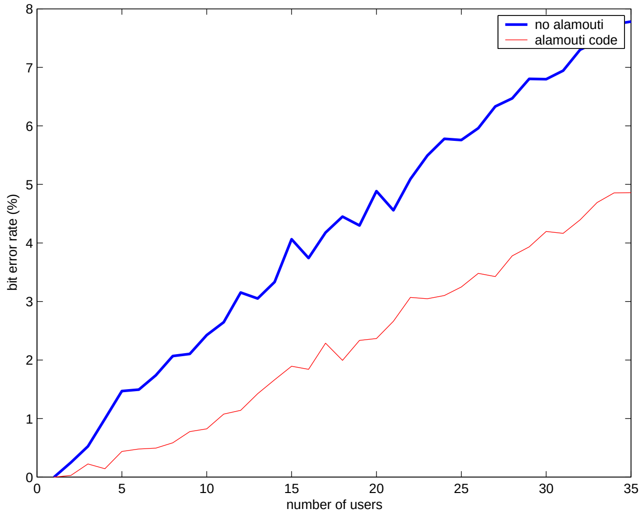

Figure 4.1: average BER - one cell (async)

capacity as the average BER does not reflect the way the BER is distributed amongst the users : at an average BER of 2% some of the users are certainly in outage!

4.2.2.2 Outage and capacity

From the plots in Figure 4.2 we can see that the use of the Alamouti code approximately doubles the system capacity. That is, if we want a BER above 2% with an availability of 85%, the number of active mobiles that are allowed in the system with the Alamouti transmit diversity technique (10 users) is around double that of the standard CDMA system (4 users). We can conclude that in a single cell system when the users transmit asynchronously, the use of Alamouti code performs around twice better than without it in terms of capacity.

4.3 Multiple cells

4.3.1 Synchronous case

Users transmitting in a synchronous way will not experience intra-cell interference but interference caused by users from other cells.

4.3.1.1 Average BER

The results of simulations with 7 and 9 cells are plotted in Figure 4.3.

From these plots we can see that, as expected, the average BER increases with the number of users (and hence the inter-cell interference) both with and without the

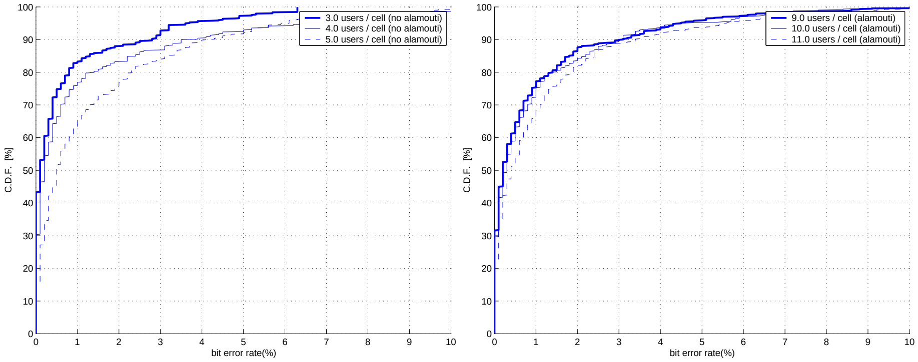

Figure 4.2: capacity - one cell, w/o and with Alamouti code (async)

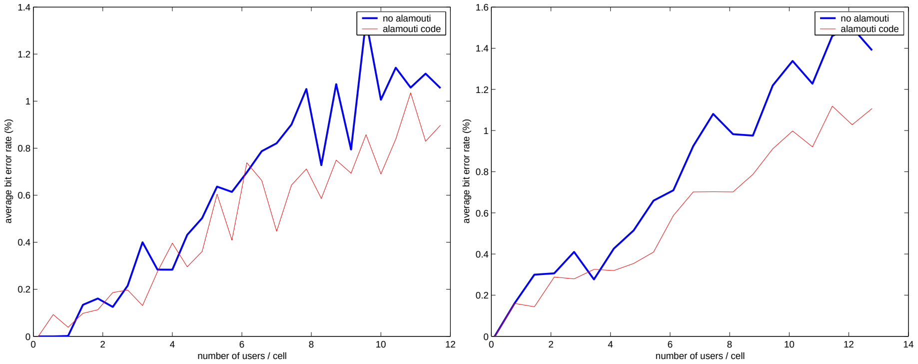

Figure 4.3: average BER - 7 cells left, 9 cells right (sync)

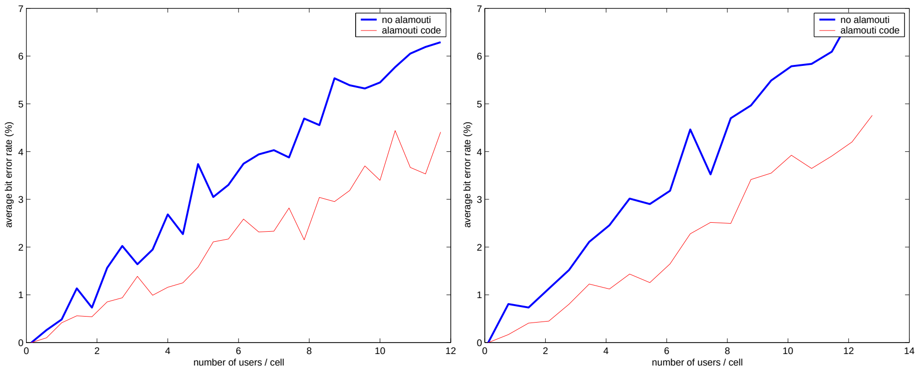

Figure 4.4: average BER - 7 cells left, 9 cells right (async)

use of STD. However, whatever the load on the network, the results with Alamouti's technique are consistently better than those with a SAS system. As the synchronous scenario is not a likely one in a real-life situation, the study of the capacity was done only for the asynchronous case and it is presented in the following paragraph.

4.3.2 Asynchronous case

When transmitting asynchronously, the users will experience both inter-cell and intra-cell interference. As seen in 4.2.2, the asynchronous transmissions break the orthogonality of the PN codes and lead to intra-cell interference.

4.3.2.1 Average BER

The results of simulations with 7 and 9 cells are plotted in Figure 4.4. If we look at an average bit error rate of 2%, we find that in the SAS case we can have approximately 4 users in the system while in the STD case we can have around 6 users in the system. This concurs with the theoretical results derived in Section 2.4.3.2.

4.3.2.2 Outage and capacity

Figures 4.5 and 4.6 allow us to see the capacity of our system in a 7 and 9 cells environment without and with the use of the Alamouti diversity technique. It is interesting to note that the 7 cells configuration gives approximately the same results as with 9 cells, so future measurements could be done using 7 cells instead of 9 to reduce computational complexity. In both cases we get a capacity of 2 users per cell in a plain CDMA system and around 4.5 users per cell with the use of the diversity technique, so the STD once again gives us a twofold increase in capacity. Compared to the single cell environment the capacity has been halved, which shows that inter-cell interference contributes in a significant fashion in limiting the capacity of the system. A better

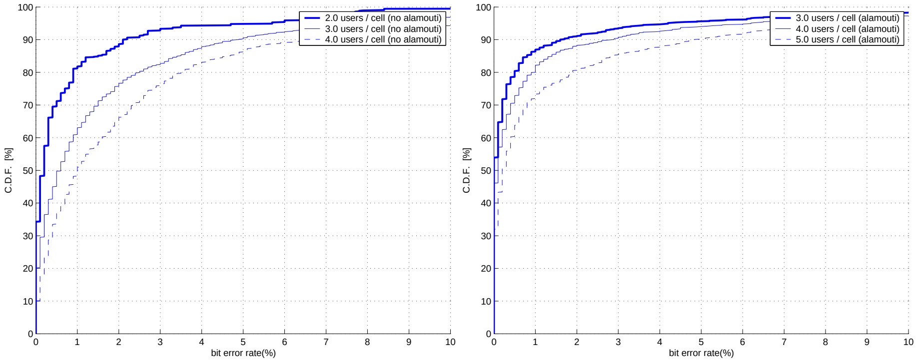

Figure 4.5: capacity - 7 cells, w/o and with Alamouti code (async)

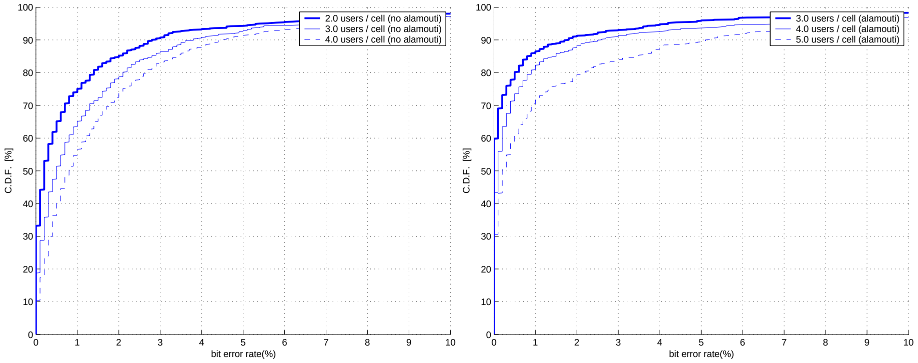

Figure 4.6: capacity - 9 cells, w/o and with Alamouti code (async)

power control algorithm combined with the use of scrambling codes would probably increase the system capacity a good deal.

Chapter 5

Conclusions and future work

5.1 Conclusions

In this work we compared two different systems: a standard CDMA system and the same system with Alamouti's transmitter diversity technique. Using a simulation tool we wrote, we ran simulations for a single cell, 7 and 9 hexagonal cell networks, both in the case where users transmit in synchronised and unsynchronised fashion. The BER measurements we obtained allowed us to determine both the average bit error rate on the links and the capacity for a fixed BER threshold and availability requirement.

For a single cell system with synchronous transmission we verified that the BER was 0% for any number of users (up to 64 users per cell) with or without transmitter diversity, due to the spreading codes' orthogonality. We also established that in the more realistic scenarios with multiple cells and asynchronous transmission, both inter-cell and intra-cell interference severely limit the cell capacity. For these cases, we found that the use of the Alamouti transmitter technique lead to a substantial improvement both in terms of average BER and in terms of capacity, yielding almost twice the capacity of the single antenna system.

5.2 Further work

As our study focused on the effect of interference, we neglected additive noise, but further results could be obtained by including the noise term and studying its effect on the capacity. This would however mean that the cell radius, the propagation gain constant and the actual power transmitted by the users need to be examined in more detail. Indeed, in our system the actual value of the power transmitted by the users is not important, only the ratio between the power received from the different users matters : if we multiply all the transmit powers by a constant we get the same bit error rate.

In order to minimise the interference between the users in our system, the power control algorithm could also be reworked, for example by implementing Distributed Constrained Power Control (DCPC). Another way of reducing the experienced interference, specifically inter-cell interference, is the use of long spreading codes (scrambling codes) on top of the channelization codes to separate traffic from the different cells. This can be easily achieved with the spreading and despreading functions we implemented.

Finally, we assumed perfect channel knowledge, which in practical situations is hard to achieve. A faulty channel estimation would most likely result in the Alamouti combining scheme introducing errors, thereby limiting the diversity gain.

Bibliography

[1] S. M. Alamouti, “A simple transmit diversity technique for wireless communications,” IEEE J. Select. Areas, Vol 16, No. 8, pp. 1451-1458, October 1998.

[2] J. Zander and S.-L. Kim, “Radio Resource Management for Wireless Networks,” Artech House Publishers, 2001.

[3] L. Ahlin and J. Zander, “Principles of Wireless Communications,” Studentlitteratur, 1998.

[4] S. Ben Slimane, “Lecture Notes of Wireless Networks,” S3, KTH. `http://www.s3.kth.se/radio/COURSES/WNETWORKS_2E1512_2003`

[5] S. Ben Slimane, “Lecture Notes of Advanced Communication Theory,” S3, KTH. `http://www.s3.kth.se/radio/COURSES/ADCOM_2E1435_2003`