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The Plausibility of implementing Receive Antenna Diversity in the Downlink of CDMA450 system

Master Thesis

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1. Table of Contents

2. List of Figures

3. List of Tables

4. List of Abbreviations

3G	Third Generation
VoIP	Voice over Internet Protocol
3GPP	Third Generation Partnership Project
HSPA	High Speed Packet Access
CDMA	Code Division Multiple Access
ADC	Analog-to-Digital Converter
SNR	Signal to Noise Ratio
MRC	Maximal Ratio Combining
CDF	Cumulative Distribution Function
XPD	Cross-Polarization Discrimination
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
2G	Second Generation
IS-95	Interim Standard-95
1xRTT	One times Radio Transmission Technology
EV-DO	Evolution-Data Optimized
EV-DV	Evolution-Data and Voice
LTE	Long Term Evolution
TTI	Transmission Time Interval
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
NLOS	Non-Line-Of-Sight
MIMO	Multiple-Input and Multiple-Output
EMI	Electromagnetic Interference
i.i.d.	Independent and identical-distributed
BTS	Base Transceiver Station

1. Introduction

1.1 Background

In later years, mobile communications have witnessed explosive growth, and the services are becoming more complex at the same time as they become cheaper. Digital mobile phone system were introduced first in 1991 allowing only voice services, and during the two last decades, they have evolved resulting in high speed data communications, and what is actually know as the third generation of telecommunication standards (3G). Mobile phones now can also be used for applications such as web browsing, Voice over Internet Protocol (VoIP), video calls, video broadcasting, etc, applications which require high data speeds connections. The Release 7 of 3GPP, the Evolved HSPA, provides a theoretical download peak of 42 Mbit/s [1], and there are different technical issues to deal if it is desired to achieve such speed connections with reasonable efficiency.

Fading is used to describe the fluctuations of the amplitudes and phases of a radio signal. When these fluctuations occur over a short period of time or travel distance, it is called small-scale fading [2]. In certain circumstances, the envelope of the received signal can be described by some distributions, like the *Ricean distribution*, in which a dominant stationary signal is received, or the *Rayleigh distribution*, used in a scenario where there are no line-of-sight between transmitter and receiver.

The fluctuations described by fading degrade the channel quality, making it hard to achieve the transmission rates required. Taking this into account, a good choice, at a low cost are the signal processing techniques like channel coding, equalization and diversity.

These techniques require additional hardware in the receiver and sometimes in the transmitter but only in those which are wanted to be more efficient, and not always they are useful, only under certain circumstances they will improve the signal enough to worth it. Diversity is a technique which can be used modifying only the mobile station, and it can introduce a good improvement of the link. This thesis aims at studying how diversity can improve a communications link, and which is the best implementation under the circumstances that will be treated.

1.2 Motivation

The goal of this thesis is to improve a wireless CDMA link of 450 MHz in a rural environment applying diversity at the mobile station. The practical application is to enhance the communications of heavy machinery in the forest industry: For example, the tree cutters are spread in a forest, and cut trees at a high rate, each one different kind of trees in different locations. It is desirable that they can communicate easily how many and which trees have cut so a lorry can take the trunks and sort them attending its quality in an efficient way.

As these mobile stations will be mostly far from the base station, the distance will insert loss to the received signal, also the vegetation in the forest will degrade the signal. The 450 Mhz band is a good choice for this purpose, as being a low radio frequency, it achieves better coverage than higher frequencies. However, at lower frequencies, the maximum data rate decreases, and the available bandwidth is restricted because each user has to share the portion of the spectrum assigned by the regulatory regime with the rest of users.

Diversity consists in improving the reception of the signal, by using multiple channels of communication. Different channels of communications can be made up with different frequency bands, which is called *frequency diversity*, or transmitting the signal in different time instants, which is called *time diversity*. But the radio spectrum is a limited source, the regulation specifies how much bandwidth is assigned, and the time diversity would decrease the channel efficiency. Therefore, the *antenna diversity* is a common method to improve the channel quality, which includes the *spatial diversity*, *polarization diversity*, and *pattern diversity*.

Antenna diversity is a cheap method that requires at least two antennas, one receive chain and an analog-to-digital converter (ADC) per antenna, and a RAKE receiver, as seen in figure 1.1. Therefore it is possible to deploy it modifying only the mobile stations desired keeping the same configuration for the base stations. Also it is worth to mention that antenna diversity is very common diversity scheme in base stations unlike in mobile stations, where the dimensions restrictions make hard to implement.

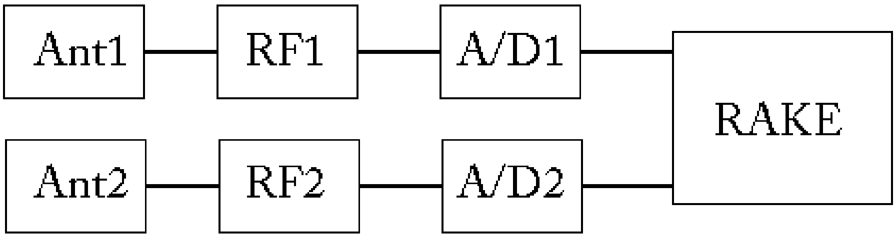

Figure 1.1 - Hardware in a diversity receiver

1.3 Problem definition

This thesis aims at evaluating how much improvement can be achieved using diversity to increase the maximum capacity of the link described above, also to find out the best way to achieve it.

The mobile station is placed on heavy machinery, therefore the receiver may be large enough to make possible the use of either spatial or polarization diversity. In a rural environment, like a forest, polarization diversity will not be as efficient as in an urban environment, due to the fact that in a city there are more random reflections, and the received signal is more independent from the transmitted signal. Also, it is not known how much should be the space between antennas to achieve a correlation coefficient below 0.7, and obtain efficient spatial diversity.

As stated before, diversity will be applied at the mobile, not at the base station, and most of the measurements have been done at the base station. It is known that at the base station it would be needed a spacing between antennas of at least 25 wavelengths [3], and at the mobile station it is supposed to be less since the signal arrives from a wider angle to the mobile.

Thus, it would be needed to take some measurements with two orthogonal antennas, and with two antennas spaced different lengths. Once the measurements were been taken, the signal correlation coefficient of each deployment could be computed, hence it would be possible to decide which solution is the best.

2. Diversity theory

Unlike wired channels, which are predictable, radio channels are mostly random, and their analysis is typically statistical. Modelling radio channels is based on measurements of specific deployments. As an example, the widely known Hata model [4] is an empirical formulation of the graphical path loss data provided by Okumura, and is valid in an urban outdoor environment with frequencies between 150 Mhz and 1500 Mhz.

Regarding the instantaneous received power, two different propagation behaviours can be noticed:

1. Variations of the received power over large distances between transmitter-receiver (about kilometres) and over large time durations (about hours). The propagation models which predict that variations are called large-scale models, and they take into account mechanism of reflection, diffraction, and scattering.

2. Variations of the received power over short travel distances (a few wavelengths) and over short time durations (on the order of seconds). These variations are characterized by the small-scale models, and are due to the interference between multiple versions of the transmitted signal that arrives at different times, the multipath waves. These waves are created by the presence of reflecting objects and scatterers in the channel. At figure 2.1 [5] can be seen the differences between both variations. Note that in small-scale fading, it can be found decreases of the signal strength greater than 20 dB within a meter. These deep fades can degrade the link, sometimes even bringing the signal strength below the minimum required level.

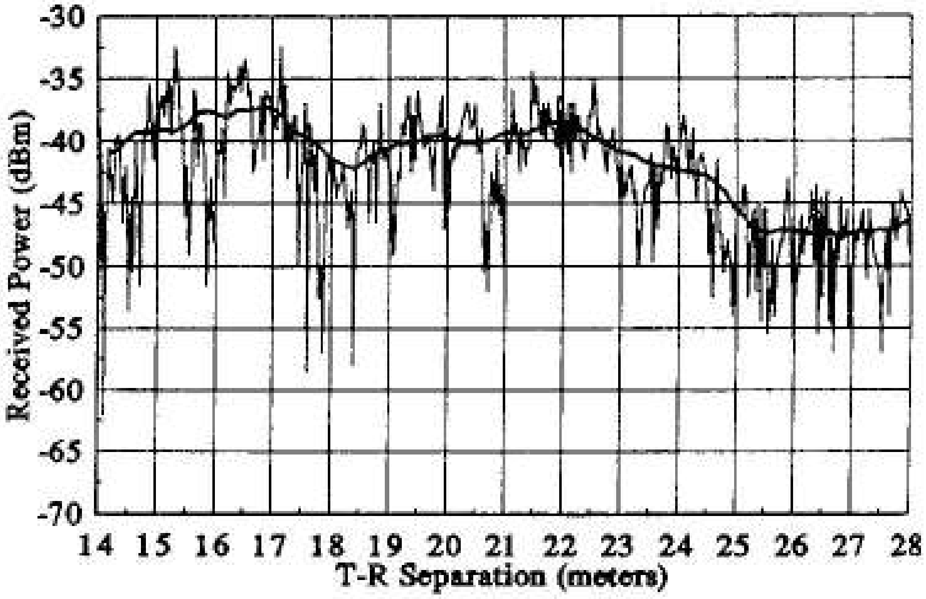

Figure 2.1 - Received Power indoors versus range in meters [4]

The following factors influence small-scale fading [2]:

1. Multipath propagation: Multiple versions of the transmitted signal with random amplitudes and phases will arrive at the receiver, which will result in fluctuations in the signal strength.

2. Speed of the mobile: When the mobile moves, the signal is random modulated due to different Doppler shifts in each component.

3. Speed of the surrounding objects: The objects in the radio channel also induce a Doppler shift on multipath components.

4. The transmission bandwidth of the signal. When the transmitted signal has a bandwidth smaller than the coherence bandwidth of the channel, the signal strength will fade.

One of the techniques used to avoid the deep fades is the diversity, which may improve the wireless link by counting the effects of multipath propagation. As the received signal will arrive trough different paths, and each path is hopefully independent, the signal might be rotated and suffer different phase and amplitude changes in each path, which means that when the signal is deeply faded at one path, another path may have a strong signal. If the paths are uncorrelated enough, with a correlation coefficient below 0.7, effective diversity can be achieved [6], [7].

2.1 Processing Methods

When using diversity, the receiver will need a combiner which selects and combines the signal from each antenna, through any method of the following categories [8]:

1. Selection diversity: The output is the input signal having the highest instantaneous Signal-to-Noise Ratio (SNR). It is easy to implement because of its low complexity, while is not the optimal technique.

   If we assume the channel to be a frequency non-selective fading channel with a coherence bandwidth much larger than the signal bandwidth, and the fading distribution function a Rayleigh distribution, the probability distribution function of the instantaneous SNR of the branch *i* is

$$P_{\Gamma i}(\gamma) = 1 - e^{-\gamma / \gamma_0}, \qquad \gamma \geq 0 \tag{1}$$

   And assuming the same average SNR in each branch, the resulting SNR becomes

$$P_{\Gamma}(\gamma) = \left(1 - e^{-\gamma / \gamma o}\right)^{M}, \qquad \gamma \geq 0 \tag{2}$$

The improvement offered by selection diversity is expressed by the average SNR:

$$\bar{\gamma} = \gamma o \sum_{k=1}^{M} \frac{1}{k} \tag{3}$$

Where γo is the average SNR for a single branch, $\bar{\gamma}$ is the mean SNR, and M is the number of independent Rayleigh channels [9].

2. Maximal Ratio Combining (MRC): This method is the one which provides the best reduction of fading, although its hardware is more complex, and it consumes more power than the other combiners.

   Once again, if we assume a Rayleigh fading channel, and i.i.d. additive noise for the different branches, the distribution function of the resulting SNR can be expressed as

$$P_{\Gamma}(\gamma) = 1 - e^{-\gamma / \gamma o} \sum_{i=1}^{M} \frac{1}{(i-1)!} \left(\frac{\gamma}{\gamma o}\right)^{i-1} \tag{4}$$

   And the mean value of the combined signal's SNR is shown at equation 5.

$$\bar{\gamma} = \sum_{i=1}^{M} \bar{\gamma}_i \tag{5}$$

   The average SNR is the sum of the SNR of each branch. So if every branch would have the same SNR, output SNR would be the SNR of one branch, multiplied by the number of antennas used for the diversity. This is achieved by weighting the signals from all the branches according to their SNR, and cophasing the signals before being summed so the sum is coherent.

3. Feedback diversity: One signal is used as output until it is dropped below a threshold, and then the output is switched to another signal.

   If we define q_x as the probability that the SNR in one branch, Γ, is below the threshold, γ_x:

$$q_x = \Pr[\Gamma < \gamma_x] \tag{6}$$

   Then the probability distribution function of the SNR is

$$P_\Gamma(\gamma) = \begin{cases} P_{\Gamma1}(\gamma) - q_x + q_x P_{\Gamma1}(\gamma), & \gamma > \gamma_x \\ q_x P_{\Gamma1}(\gamma), & \gamma \le \gamma_x \end{cases} \qquad (7)$$

4. Equal gain diversity: The input signals are added directly, which may provide an acceptable signal from unacceptable inputs. The mean SNR for an M-branch scheme in Rayleigh fading channels is

$$\bar{\gamma} = \gamma o(1 + (M - 1)\frac{\pi}{4}) \qquad (8)$$

At figure 2.2 is shown the probability distribution function of the selection combining, MRC and switched combining for a two branched diversity. The diversity gain is defined as de decrease in SNR compared to a non-diversity receiver for a given performance factor [10], which can be seen in the figure as the difference in dB between a combining method and the one-branch function for a given probability.

Note that the best combining method is MRC, which is about 1 dB better than selection combining. For switching combining, the probability distribution function is shown for two different thresholds, 10 and 15 dB lower than the mean SNR of one branch.

The previous analysis is based in the assumption that the fading signals in each branch are uncorrelated. In practice, there will be some correlation between the branches, and the instantaneous SNR gain of diversity will be lower.

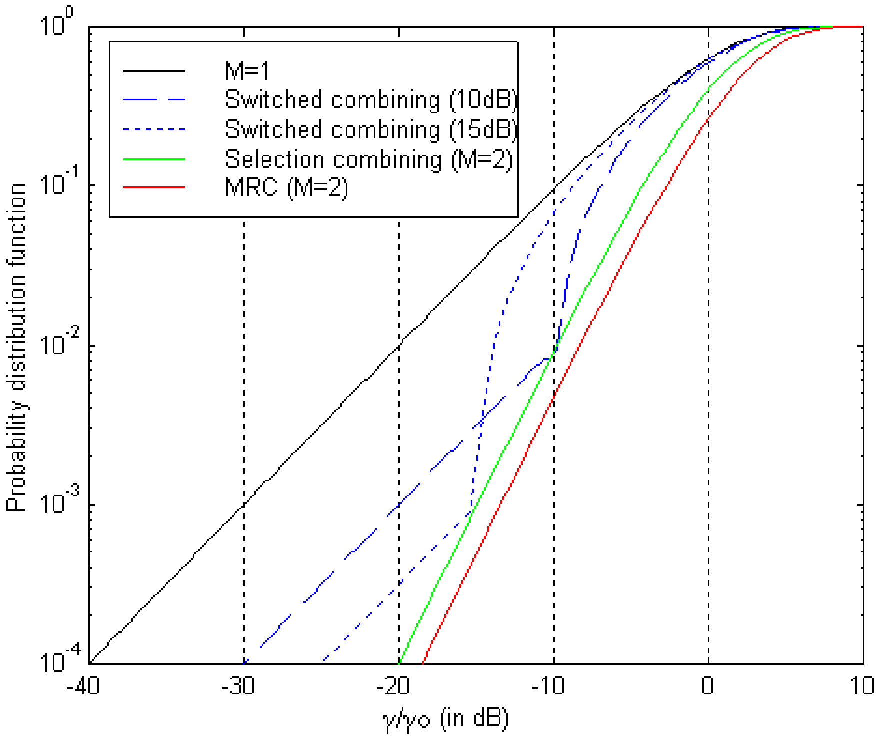

Figure 2.2 - CDF of a two-branch diversity scheme

2.2 Antenna Diversity Techniques

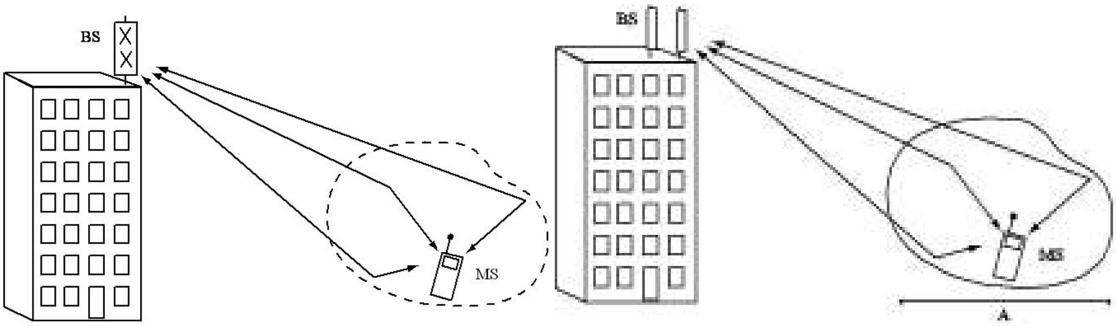

Figure 2.3 - Polarization (left) and space diversity (right) [11]

Among all the techniques of diversity, this thesis will focus only on two of the multi-antenna techniques, the spatial and polarization diversity.

2.2.1 Space diversity

Spatial diversity consists in having multiple antennas spaced a certain distance, so the paths will be different. Obviously, if they are not spaced enough, signals will be too similar to accomplish efficient diversity, since they have a high correlation coefficient. It can be shown [12] that in a situation in which the received signal consists of a large number of signal components with approximately equal signal levels, the correlation is given by equation 9 and it is plotted on figure 2.4:

$$\rho = J_0^2\left(2\pi\frac{d}{\lambda}\right) \tag{9}$$

where $J_0(\cdot)$ is the first kind Bessel function of zero order, d is the space between antennas, and λ is the wavelength of the signal.

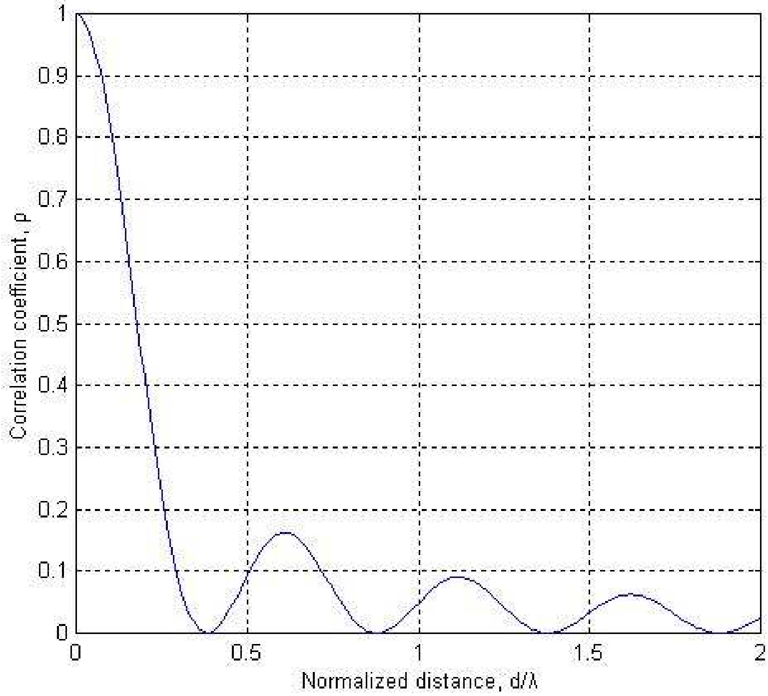

Figure 2.4 - Correlation as a function of normalized distance

Note that with a separation slightly lower than half a wavelength, a correlation coefficient close to zero can be obtained. In a 450 MHz system, it would be about 30 cm of separation between antennas to obtain uncorrelated signals. In practice, however, the required separation will be larger.

At some applications it is impossible to have the required separation, in which the use of polarization diversity is the best choice. However, although in polarization diversity antennas can be co-located, it can only provide two diversity branches.

2.2.2 Polarization diversity

Polarization diversity consists in receiving the signal through two orthogonal antennas when it is transmitted with linear polarization. It makes sense if we take into account that sufficient random reflections in the channel will cause the received signal to have a polarization state that in the best case is almost completely independent from the transmitted signal, since there is always some dependence between them [13].

The arriving signal at the receiver in each polarization can be expressed as

$$x = r_1 \cos(\omega t + \phi_1) \tag{10}$$

$$y = r_2 \cos(\omega t + \phi_2) \tag{11}$$

Where x and y are signal levels which are received when $\beta = 0$.

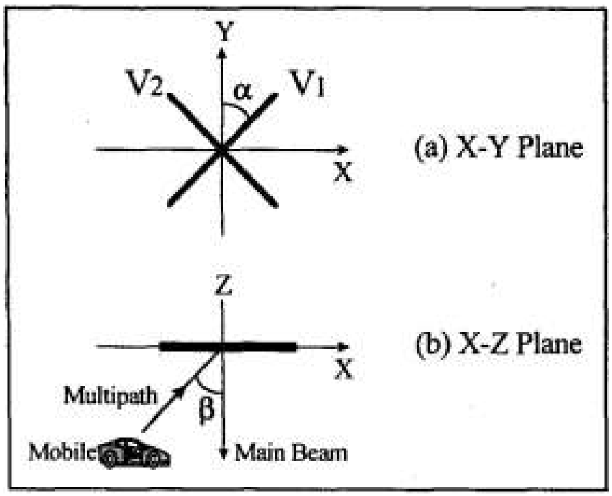

Figure 2.5 - Typical model for base station polarization diversity [14]

The received signal at elements V_1 and V_2 can be written as:

$$V_1 = (ar_1 \cos\phi_1 + r_2 b \cos\phi_2)\cos\omega t - (ar_1 \sin\phi_1 + r_2 b \sin\phi_2)\sin\omega t \quad (12)$$
$$V_2 = (-ar_1 \cos\phi_1 + r_2 b \cos\phi_2)\cos\omega t - (-ar_1 \sin\phi_1 + r_2 b \sin\phi_2)\sin\omega t \quad (13)$$

where $a = \sin\alpha\cos\beta$ and $b = \cos\alpha$.

The correlation coefficient ρ can be written as

$$\rho = \left(\frac{\tan^2(\alpha)\cos^2(\beta) - \Gamma}{\tan^2(\alpha)\cos^2(\beta) + \Gamma}\right)^2 \quad (14)$$

where

$$X = \frac{E\{R_2^2\}}{E\{R_1^2\}} \quad (15)$$

where $E\{\cdot\}$ means expectation value over time, X is called *cross-polarization discrimination* (XPD), and

$$R_1 = \sqrt{r_1^2 a^2 + r_2^2 b^2 + 2r_1 r_2 ab\cos(\phi_1 + \phi_2)} \quad (16)$$
$$R_2 = \sqrt{r_1^2 a^2 + r_2^2 b^2 - 2r_1 r_2 ab\cos(\phi_1 + \phi_2)} \quad (17)$$

Polarization diversity is the dominant base station diversity method in mobile communications, and many measurements of the XPD have been taken in different scenarios, with different frequencies and different mobile orientation. At table 1 is shown the results of some measurements in different environments.

Environment and source	Mobile orientation	XPD (dB)	Frequency	Correlation between vertical and horizontal field ρ_{env}
Urban[14]	Vertical car antenna	4-7	920 MHz	0.02 median
Urban[15] Sub-urban[15]	30° on large groundplane	7 12	463 MHz	-0.003 0.019
Urban & Sub-urban[16]	0° 45°	10 4.6-6.3	1790 MHz	<0.7 for 95% <0.7 for 95%
Urban[17] Sub-urban[17]	70 ±15 deg in- an outdoor	1-4 2-7	1821 MHz	<0.2 for 90% <0.1 for 90%
Urban & Sub-urban[18]	0° 45°	4-7 0	1848 MHz	<0.5 for 93% <0.5 for 93%
Urban[18]	Car mounted monopole	7.6±2.1	970 MHz	0.09±0.09
Urban & Sub-urban[19]	Random, in- and outdoor	<5	1739 MHz	-0.25 to 0.24
Sub-urban[21]	Vertical mobile LOS & NLOS	7	1800 MHz	< 0.2 average
Urban & Sub-urban[22]	Vertical dipole	8-11	900 & 1800 MHz	< 0.7 all values
Urban[21] Sub-urban[21]	Vertical monopole	5 10	1800 MHz	-

Table 1 - Typical values of XPD and correlation in urban and sub-urban environments. [11]

There are some other considerations to think of when choosing between both spatial and polarization diversity. As said before, only if sufficient random reflections are suffered by the signal, polarization diversity is efficient, and it is obvious that it will occur mainly in urban environments although it happens less deeply in sub-urban or rural environments. It is also good to know that when using MRC, the diversity gain is invariant to the rotation of the antennas [23], in other cases ±45° polarization provides better performance than horizontal/vertical [24]. Regarding the spatial diversity, it turns out that at the base station the signal will come through a narrow angle due to the fact that reflections happen mostly in the vicinity of the mobile (figure 2.3). It leads to large spacing between antennas in the base station, unlike the mobile, at which the signal comes from a wider angle. Also, has been noticed that spacing is not required to be as large for vertical spacing as it is for horizontal spacing [25].

3. CDMA

3.1 The CDMA method

In a radio system there are two resources to transmit the information: time and frequency. When several users have to communicate, it is possible to split the available spectrum in channels, so each pair of communicators can use part of the spectrum to transmit and receive. That is called FDMA (Frequency Division Multiple Access). Also it is possible to assign a time interval for each pair of users, which is called TDMA (Time Division Multiple Access). In CDMA every user is allocated the entire available spectrum at all the time, and the identification is done by means of a unique code for each user (figure 3.1).

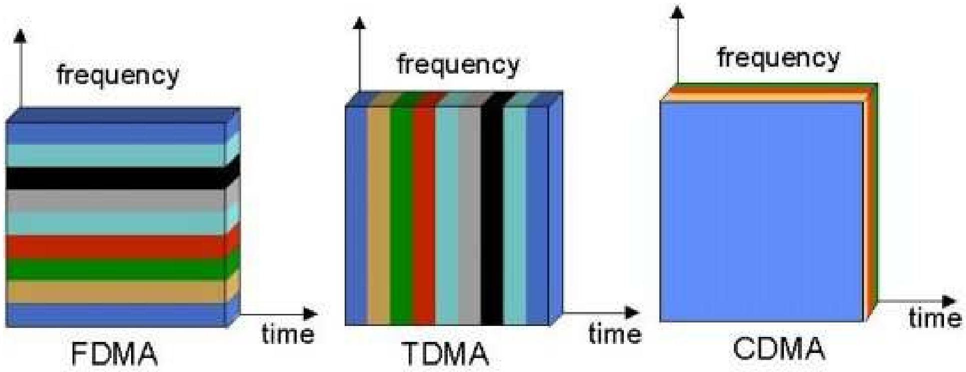

Figure 3.1 - Access technologies in radio systems

If used properly, the three of them have theoretically the same spectrum efficiency, but in practice, for FDMA are needed some filters to select the channel, and as the filters have a finite slope the whole spectrum can not be fully used. Something similar will happen with TDMA, there has to be a small time guard between bursts to assure that different bursts of data do not mix up. Therefore CDMA is the channel access method which can easily achieve higher spectrum efficiency.

For each channel it is possible to define the *coherence bandwidth*, which is a measurement of the range of frequencies over which the channel can be considered coherent. Also, it is defined the *coherence time,* the time interval over which the channel can be considered coherent. It means that any signal longer than the coherence time, or wider than the coherence bandwidth, would be affected by the multipath propagation.

CDMA uses a spread spectrum technique (see figure 3.2) and hence the signals will have a bandwidth typically greater than the coherence bandwidth, and it is likely to be affected by multipath propagation. FDMA and TDMA are, however, narrow band systems.

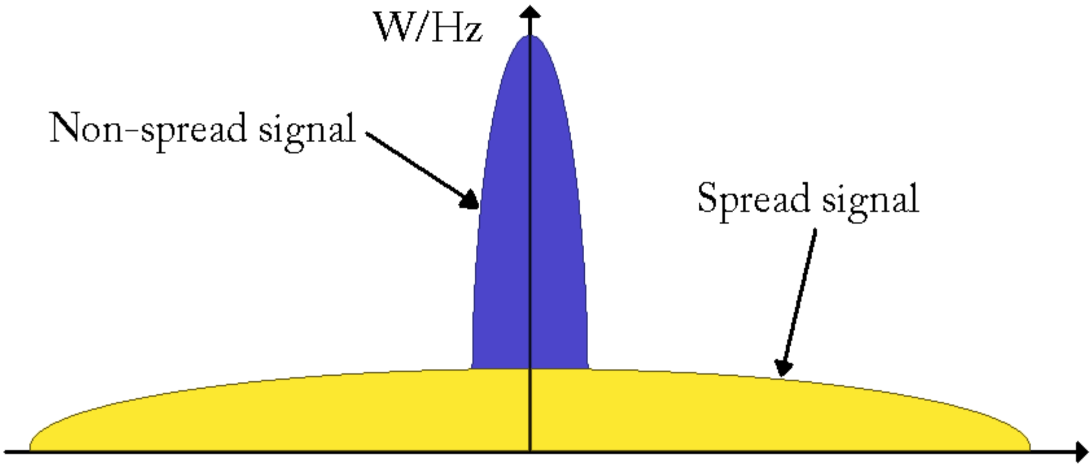

Figure 3.2 - Spread and Non-spread signals

3.2 The RAKE receiver

The RAKE receiver is responsible for counteracting the effects of multipath increasing the SNR. Basically, it mixes the signals received in each path to obtain a stronger signal.

The RAKE receiver provides a separate correlation receiver for each multipath signal, these are called *fingers*. Each finger detects a version of the original transmission, and then it is weighted and added to the other finger's output (figure 3.3).

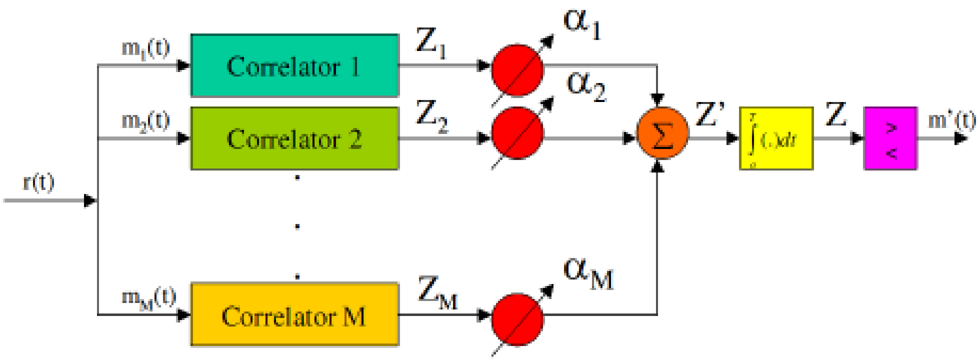

Figure 3.3 - Block diagram of a M-branch RAKE receiver

3.3 The cdma2000 standards

The cdma2000 standards are direct successors to the 2G standard IS-95, which unlike other 2G standards uses CDMA (Code Division Multiple Access) as a channel access method.

There are three types of cdma2000:

1. 1xRTT: The first commercial service was launch at the year 2000. It uses a duplex pair of 1.25 MHz radio channels, and can achieve a peak of 144 kbit/s in the downlink and uplink channels. The other two types of cdma2000 are parallel evolutions of this standard.

2. EV-DO: The first commercial service was launch at the year 2002. Many revisions of this standard were done, and with the last one, it is possible to achieve a peak of 9.3 Mbit/s.

3. EV-DV: Supports downlink data rates up to 3.1 Mbit/s, and uplink data rates up to 1.8 Mbit/s. This standard was less attractive to operators than EV-DO, and was not implemented.

EV-DO

It is standardized by 3GPP2 (3rd Generation Partnership Project 2) with the purpose of obtain high data rates. It has been adopted by many mobile phone providers, mainly by those previously employing IS-95. It went through 4 evolution steps in Rev 0, Rev A, Rev B and Rev C. This last one was proposed as the natural evolution path for cdma2000, but the development of this technology was ended in favour of the competing standard LTE (Long Term Evolution), and no carrier announced plans to adopt it.

On Rev 0 a new uplink and downlink structure was defined in which the whole carrier works as a shared downlink resource for data transmission, hence there cannot be a simultaneous packet data and legacy circuit-switched service to the same user on one carrier. It was focused on improving the downlink channel, and it can support a peak data rate of 2.4 Mbps. Some new features were the reduction the TTI (Transmission time interval), which results in a lower latency, the increase of the modulation order to a 16QAM and the rate control through adaptive modulation and coding.

The Rev A was focused on an uplink improvement. The data peak for the uplink channel was raised to 1.8 Mbps, also a higher capacity is achieved in a more packet-oriented uplink. By means of the enhanced access channel the connection establish time were decreased, multi-user packets and QoS flags were introduced, which resulted in a low latency for low bit rate communications such as VoIP.

The next step in the standards is Rev B, which enables higher data rate by aggregation of multiple carriers. Although it permits up to sixteen 1.25 Mhz carriers to be aggregated, the devices will most likely support up to three carriers, giving a peak downlink data rate of 9.3 Mbps [26]. Also, the latency was decreased by the use of statistical multiplexing.

4. Related work

Figure 2.4 shows the envelope correlation of signals as a function of the space between antennas in space diversity. That function only applies if the antennas had pure omnidirectional patterns. But because the mutual coupling between antennas will distort their patterns, the measured correlation will be lower, especially for small spacings.

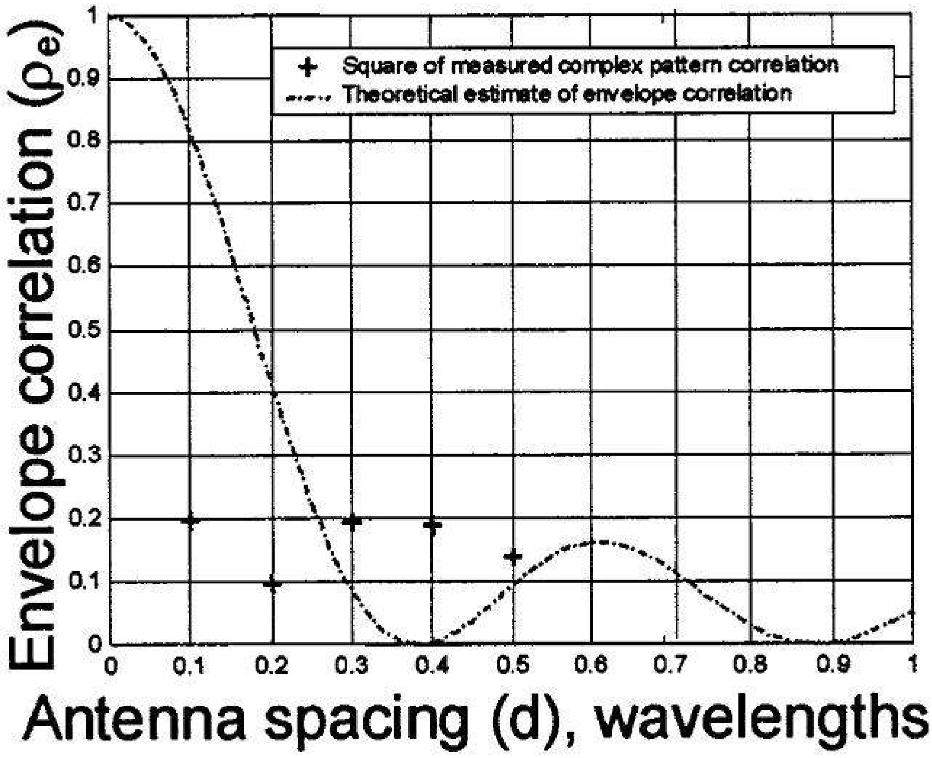

Figure 4.1 - Measured and theoretical correlation versus spacing [27]

At figure 4.1 can be seen how the measured correlation is lower than the theoretical due to the mutual coupling. These measurements were for narrow-band signals at 2.05 GHz. However, this effect is not entirely beneficial, since the distorted patterns also cause power imbalance when the multipath is not uniformly distributed in angle. This will result in a reduction of the diversity gain compared to the gain that can be achieved with omnidirectional elements and the same correlation [27].

At these measurements, envelope correlations below 0.7 were observed in all channels by all spatial, polarization, and pattern diversity configurations that had spacings greater than 0.1 wavelengths. In an NLOS (non-line-of-sight) outdoor channel, a diversity gain of 8-9 dB can be achieved with antenna spacing as small as 0.1-0.15 wavelengths [27].

Antenna Configuration	Envelope Correlation	Div. Gain in dB with max. ratio, 99% reliability	Div. Gain in dB with selection, 99% reliability
Spatial	0.29 - 0.60	6.2 – 10.6	4.6 – 9.0
Polarization	-0.052	8.6	6.8
Pattern	0.12	6.5	5.3

Table 2 - Statistics for measurements for NLOS channels in a rural environment [27]

The results at table 2 show that it is possible to obtain effective correlation with spacings of 0.25 wavelengths, and a similar gain than polarization diversity.

As a point of interest, the following measurements compare the diversity gain between spatial and polarization diversity. The diversity gain was also measured combining spatial and polarization diversity in the 900 Mhz band using dipoles. Both measurements were done in a MIMO 3x3 system [28].

Figure 4.2 illustrates a comparison between spatial and polarization diversity, where it is clearly observed that an equivalence scenario is obtained for the two diversity techniques. As an example, a spatial separation of 0.12 wavelengths is equivalent to an angular separation of 36º.

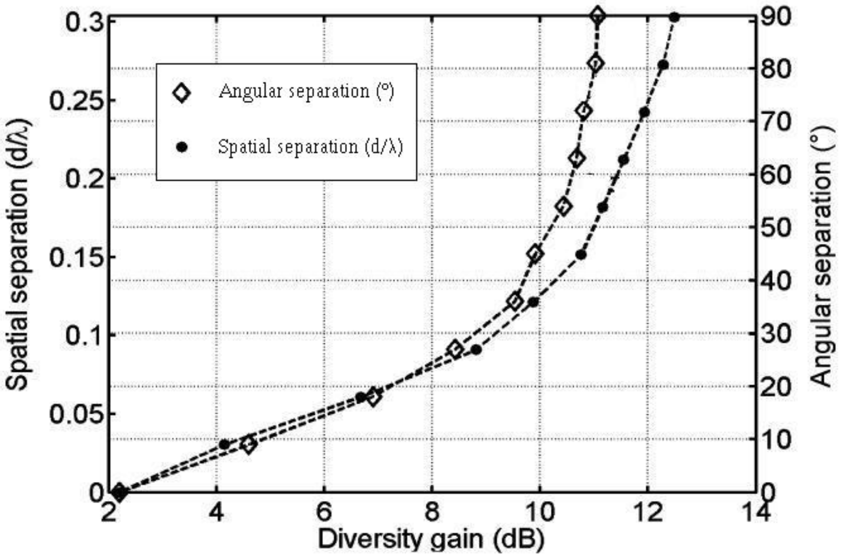

Figure 4.2 - Spatial and angular separation versus measured diversity gain

Figure 4.3 shows how the combination of both spatial and polarization diversity provided increased diversity gain. For different angular separations between dipoles (the angle is a parameter), the diversity gain is plotted, and as can be seen, when the angular separation is large, the spatial separation can hardly improve the diversity gain. Similarly, when the spatial separation is large, the angular separation can barely improve the diversity gain, and the improvement is clearly visible when the separation is small.

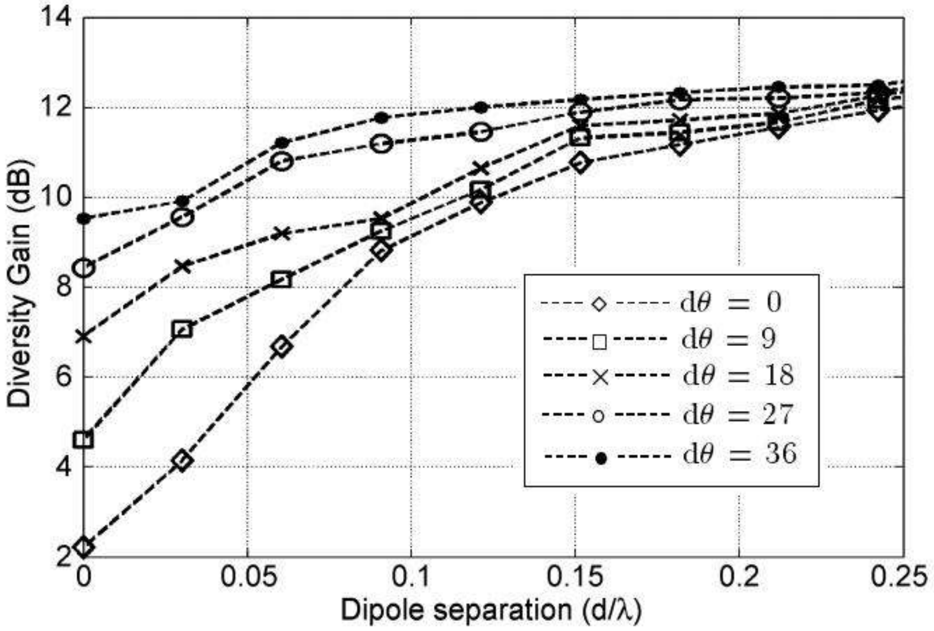

Figure 4.3 - Diversity gain versus dipole separation

About the cumulative distribution function, many measurements have been taken [29], and as an example, next figure shows the measured and predicted CDF before and after Maximal Ratio Combining in a spatial diversity system.

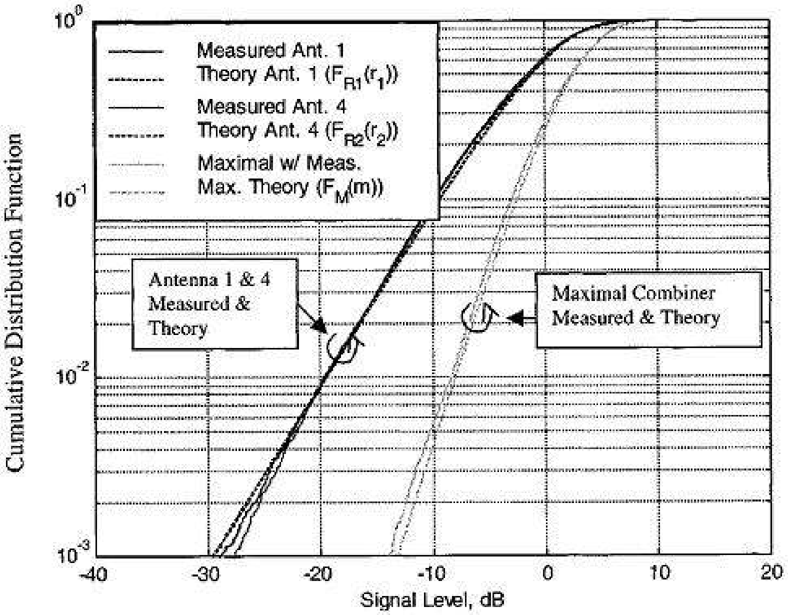

Figure 4.4 - Measured and predicted CDF before and after MRC [29]

The signals had an envelope correlation of ρ = 0.0708, and they were received with two dipoles spaced 0.6 wavelengths at 2.05 Ghz. It is clear that the difference between the improvement of the combined signal and the theoretical maximum is almost non-existing.

5. Environment Analysis

Before taking any measurement of diversity, we were able to analyze the environment where they will be taken. This is important so we can have an idea about how strong is the noise on that area and the Electromagnetic Interference (EMI) produced by the heavy machinery.

The measurements analyzed here were taken in a forest near Gävle on June 09. It was used a spectrum analyzer model **Rohde-Schwarz FSQ29**, and a Yagi-Uda antenna, apart from a computer to store the measurements. The machine producing the interference was a tree cutter which can be seen at figure 5.1.

Figure 5.1 - Location and instrumentation of the measurements

First, a measurement of the spectrum was taken in the band of 0-3 GHz. Later on, the spectrum was measured only on the band of interest, from 400 to 500 Mhz. Both of the measurements were taken pointing the antenna to the forest with the machine off, in order to have a reference of the environment without any additional interference.

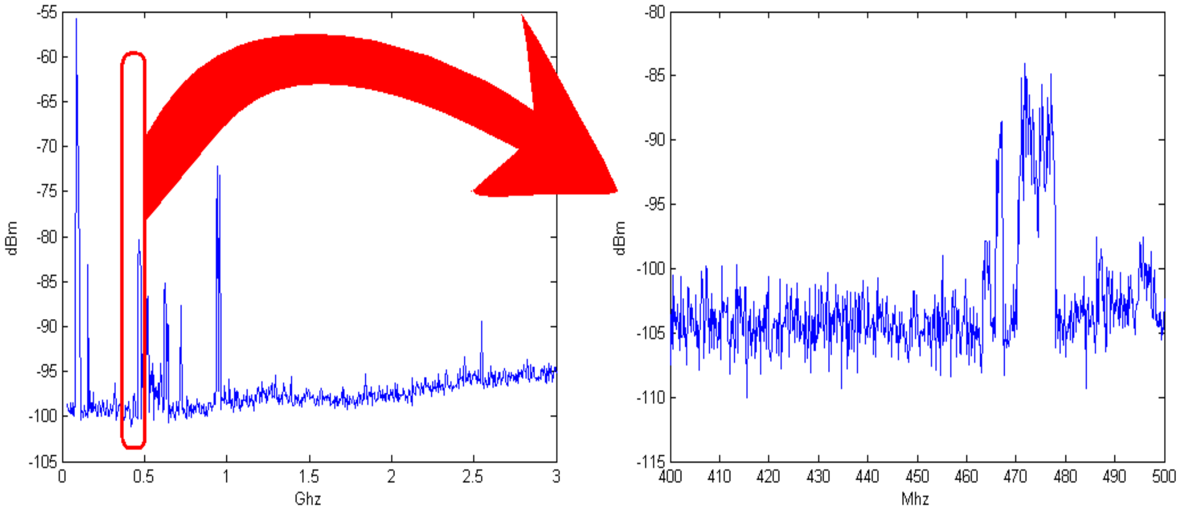

Figure 5.2 - Spectrum in the forest without any machine working

Taking a look on the zoomed graph, the interest band can be seen. There are certain frequencies, mostly around the 475 MHz where the received signal is strong, reaching -85 dBm.

Figure 5.3 shows the measured spectrum pointing the antenna at the four sides of the machine, while it was cutting trees. Note: The back of the machine is where the arm used to cut trees is placed.

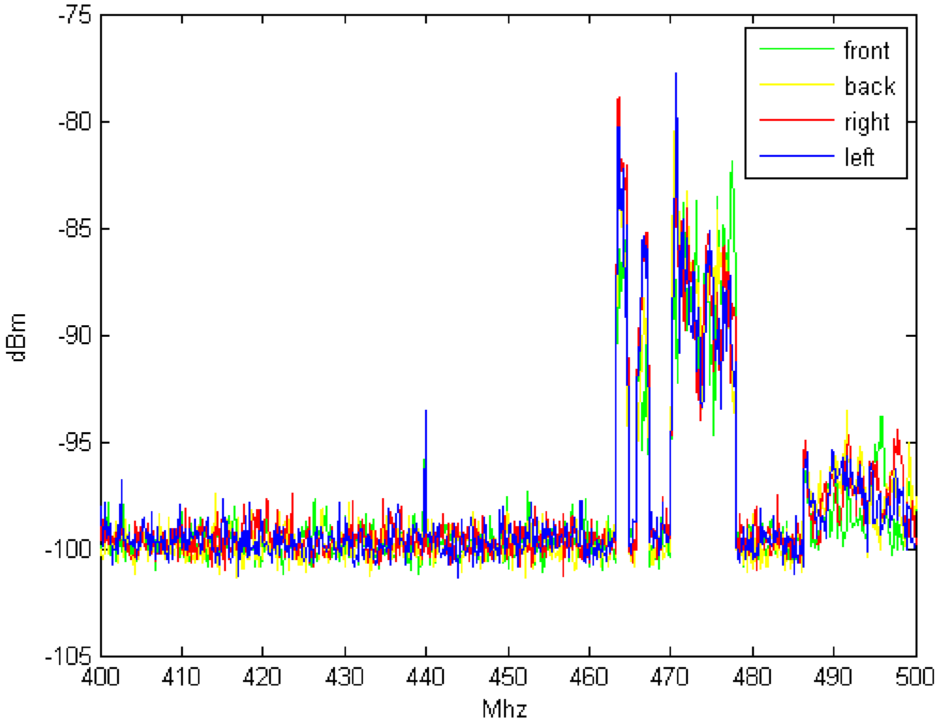

Figure 5.3 - Spectrum at each side of the machine while it was working

Although they are not exactly the same, there is barely any difference between the measurements at the different sides of the machine.

As information of interest, here is shown how many dBs are added by the machine to the environment, which is computed by subtracting the spectrum of the forest to the spectrum of the machine (figure 5.4).

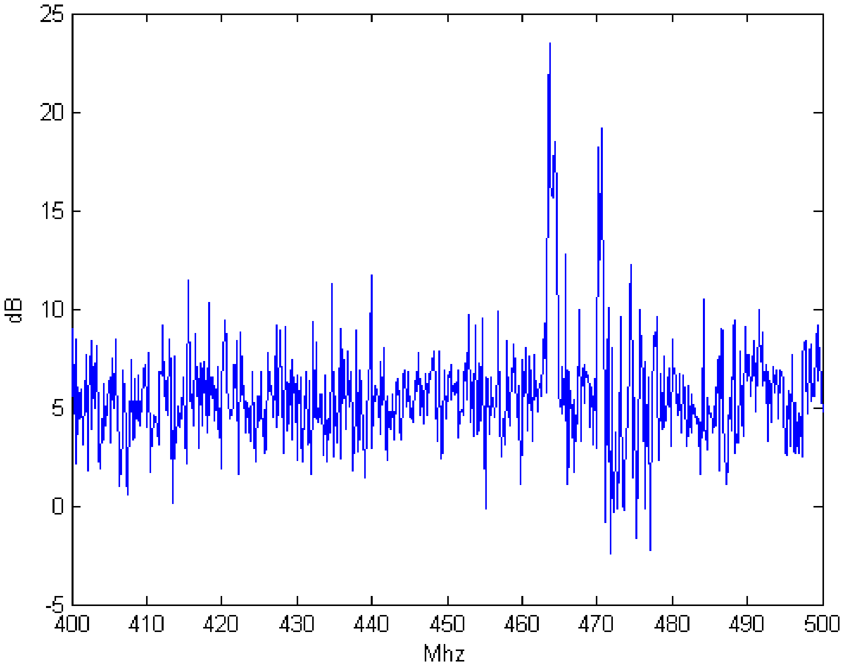

Figure 5.4 - Subtraction of the spectrum of the forest and the machine

Around 5 dB of interferences are added by the machine while working at the interest band, except for certain frequencies where it adds up to 24 dB.

Finally, the zero-span option was used to get a measurement of the signal on time. In figure 5.5 is shown the probability distribution function of that signal, which has a Rayleigh distribution due to the fact that most of the signal is noise.

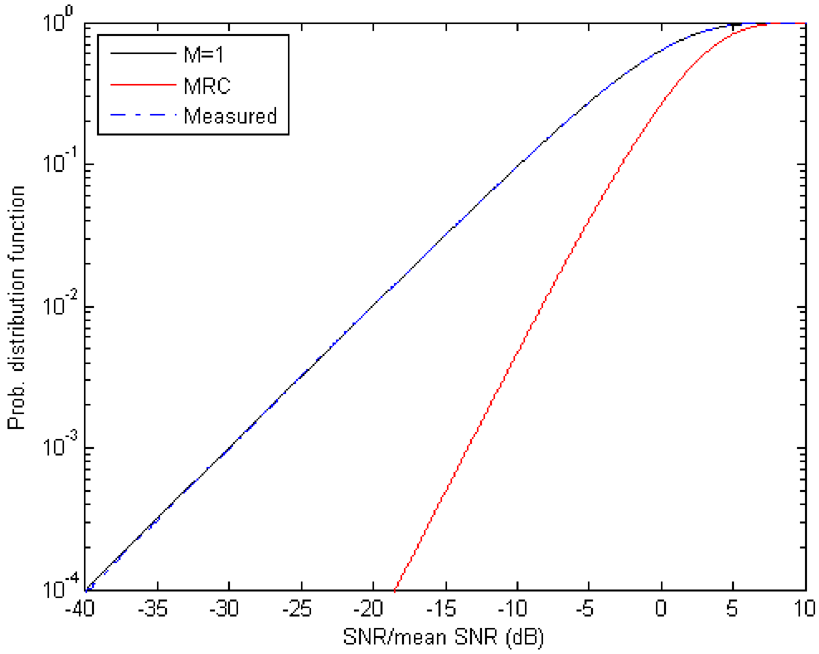

Figure 5.5 - Probability distribution function of the measurement

6. Simulation

To simulate how much improvement can be achieved using diversity, the numerical computing environment MATLAB® has been used. Many simulations were done, some of them taking several minutes to compute.

First step is to construct a Rayleigh fading channel, which is simulated in MATLAB using the model of section 9.1.3.5.2 in [30]. The model has many configurable options, among them there is the path delay vector. This vector contains the different delays for each component path of the received signal, and the maximum delay will indicate the environment of the channel, as a small delay is typical of an urban area, and a large delay is typical of a rural environment, like an area surrounded by mountains [31]. At figure 6.1 is shown a simulation of a Rayleigh channel which maximum delay is 1 μs. It is clear that a narrow band signal will not be affected by the fading as much as the spread-spectrum signal, for the coherence bandwidth of the channel is much less than the bandwidth of the spread-spectrum signal.

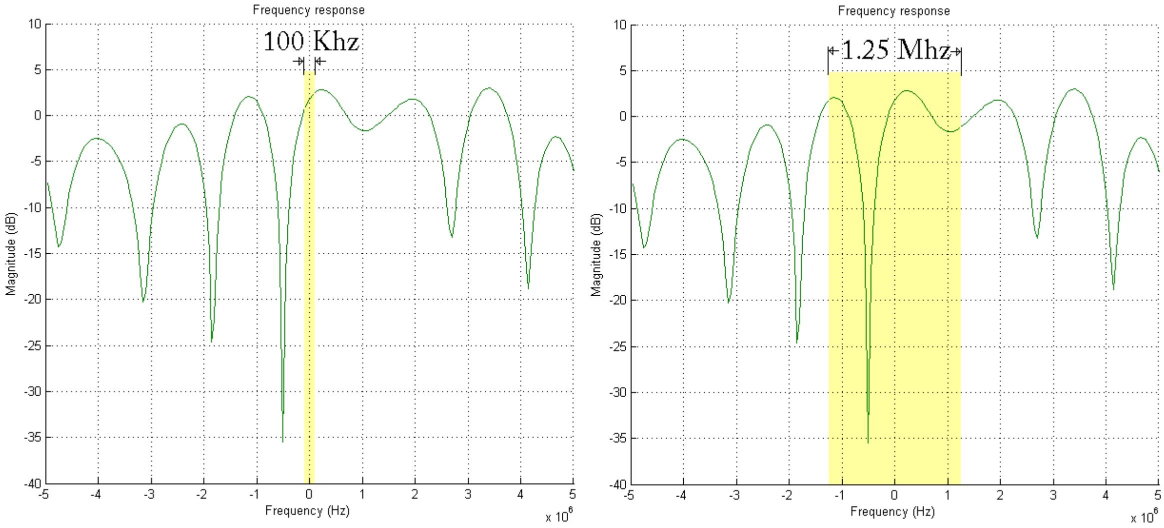

Figure 6.1 - Comparison between narrow and wide band signals.

It is important also to use a signal that resembles to a cdma2000 signal, thus the 1.25 Mhz signal will have a duration of 5, 10 or 20 ms [32]. Using a longer signal in the simulation would be affected by time changing nature of the channel. The time length of the signal should be smaller than the coherence time of the channel, thus a longer time would cause greater diversity gain.

At figure 6.2 is shown the probability distribution function of the diversity gain for a 1.25 Mhz signal of 20 ms. The signal was a stream of random bits, and the curves are similar to the theoretical ones, but as the variance is not negligible, from now on, shown results will be the average of several simulations.

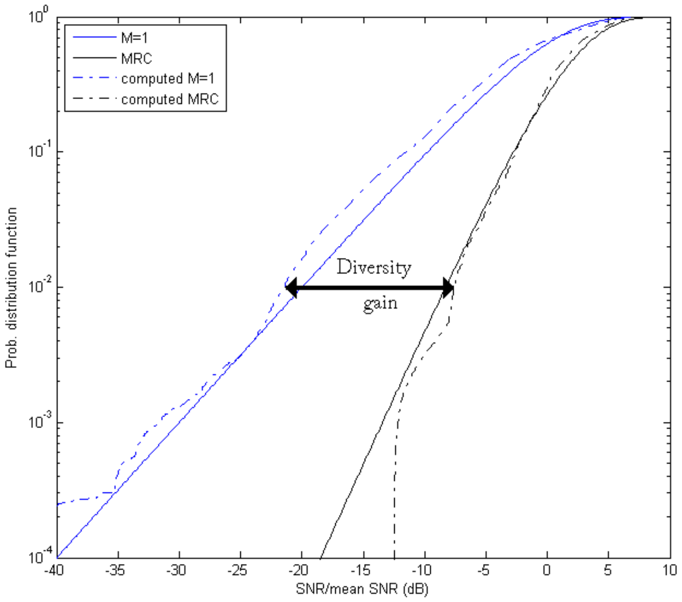

Figure 6.2 - Example of simulation: Diversity Gain

As explained at chapter 3.1, the diversity gain is achieved by spreading a narrow band signal into a wide band signal, though it is possible to have certain gain in the narrow band signal, and also to have a very low gain in the wide band signal. At figure 6.3 it is possible to see how different can be the gain for a signal of 100 Khz, and the same signal spread into a 1.25 Mhz band.

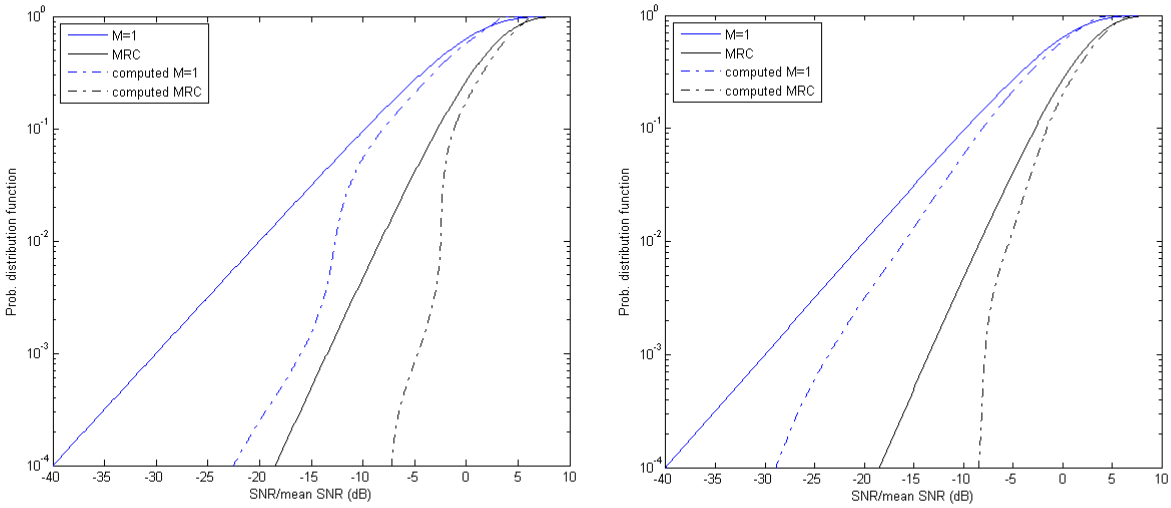

Figure 6.3 - Diversity gain in narrow and wide band signals

Both signals were modulated by a Rayleigh channel, and as expected, the results show that there is a higher probability of having higher diversity gains in wide-band signals than in narrow-band signals.

At this point it is important to remember that the Rayleigh fading has no line of sight signal, and the contributions to the received signal have different paths, each one with different time delay. The maximum time delay is called the *delay spread* D, and it defines the coherence bandwidth by means of equation 18:

$$\mathrm{BW_c} = \frac{1}{\mathrm{D}} \tag{18}$$

As the delay spread depends on the environment, it is unknown how much it is in this thesis scenario. It is known that for suburban areas it is typically between 0.1 µs and 10 µs [31]. At figure 6.4 can be seen the diversity gain of the same signal used for figure 6.3, but this time using the time delay as a parameter. Left graphic is for a narrow band signal and right for a wide band.

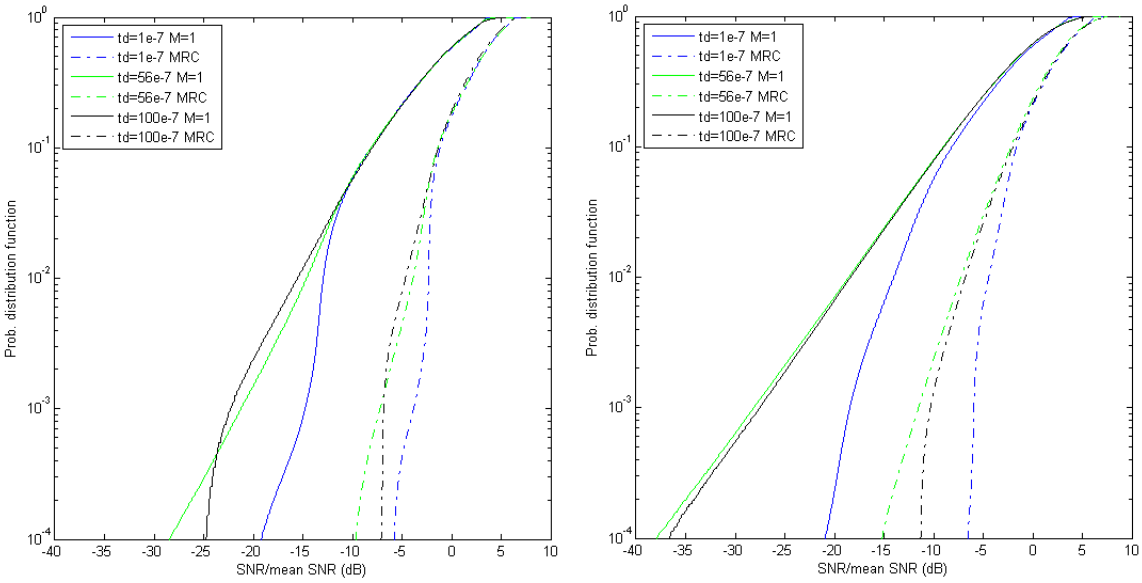

Figure 6.4 – Diversity gain with time delay as a parameter.

The probability distribution function shows the probability that the variable ‘SNR/mean SNR’ takes on a value less than or equal to the abscissa. The difference between both curves, M=1, and MRC is the diversity gain, as shown at figure 6.2, and it is obviously different for each probability. It can be noticed that the diversity gain is similar for narrow and wide band signals if the time delay is low, but for higher time delays the diversity gain raises, especially for wide band signals.

Now, if figures 2.2 and 6.4 are compared, it is clear that the signals on figure 6.4 resembles to the ones on figure 2.2. The difference between both is that on figure 2.2 the spectrum of the signals may be too narrow to have a good Rayleigh distribution. For the wide band-signals (right figure) the resemblance is greater than for narrow-band signals, also, looking at the wide-band signals, when the *delay spread* of the channel increases, the resemblance of the signals to a Rayleigh distribution also increases, and this is because the coherence bandwidth decreases, and the signal is much more affected by the Rayleigh distribution.

At figure 6.5 is plotted the gain versus the time delay, using the probability as a parameter. Once again left graphic is for a narrow band signal and right for a wide band.

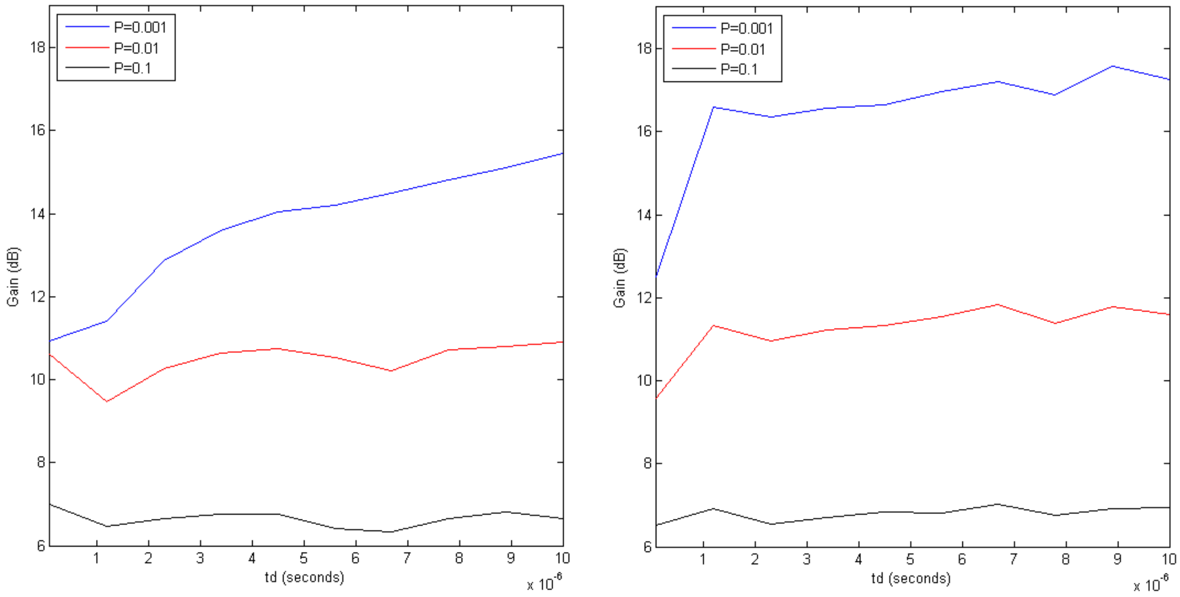

Figure 6.5 - Diversity gain VS time delay.

Logically, the probability of having greater gains (blue lines) is smaller than the probability of having low gains (black lines), it indicates that in the reception, most of the time the diversity gain will be low, and rarely will be greater than 10 dB. Also the gain increases with the time delay because two signals that have followed short paths are likely more similar than two that have followed two long paths, thus the diversity is greater for the last ones.

7. Measurements

7.1 Measurements set-up

The diversity measurements were taken in the forest between the small towns of Lingbo and Svatnäs, Sweden. The BTS is located on a hill, at coordinates (61.096143;16.573391), and the measurements were done at three points differently spaced from the BTS on the same direction (Figure 7.1). Thus the first measurement was taken at 6.45 Km from the BTS, the second at 13.69 Km, and the last one at 20.46 Km from the BTS. All three measurements were done in the forest, where we were surrounded by trees covered with snow, and it was also snowing. In the area there were some small hills, and some of them are close to the line-of-sight.

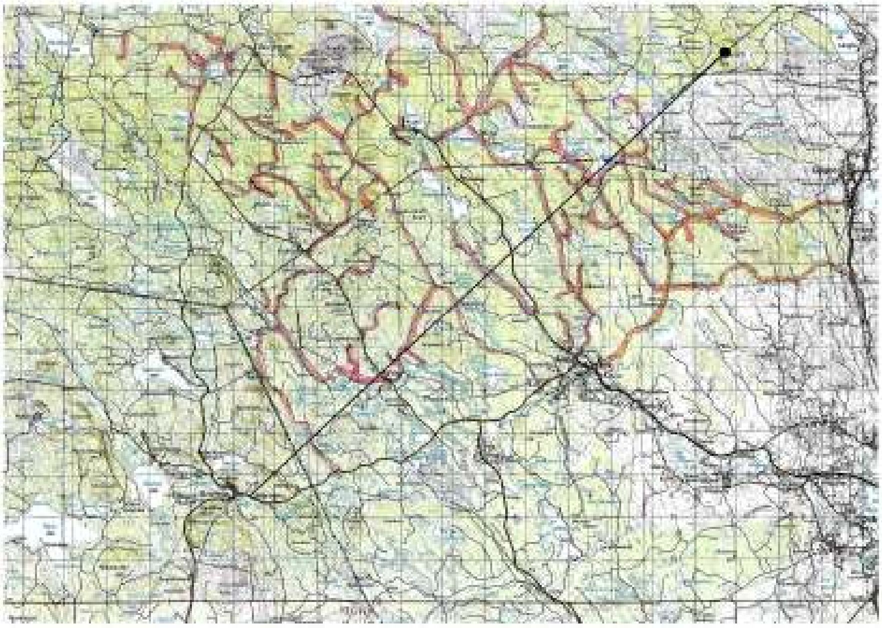

Figure 7.1 - Area of measurements

At each point it was done 12 measurements: first using just one antenna, and then, another eleven using two antennas. The antennas were placed on a wood which had equally spaced holes to place the antennas at different distances. The distance between holes was 11.27 cm, which is about one sixth of the wavelength at 464 Mhz. This frequency is the centre of a carrier in the cdma2000 standard.

The wood was mounted on the roof of a car, and the measurements were taken while the car was moving along the road to obtain signals affected by the Doppler effect (Figure 7.2). To ensure that the signal was arriving through the forest, and not through one side of the road, the roads where the measurements were taken were crossing the line from where the signal came.

Figure 7.2 - Measurements equipment

And the set-up of the equipment can be seen on figure 7.3:

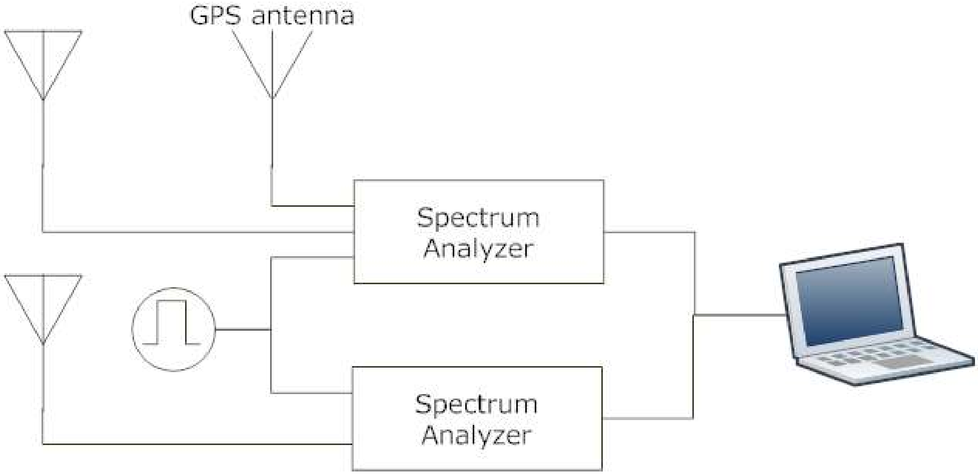

Figure 7.3 - Equipment set-up

Each antenna was connected to a portable spectrum analyzer, models Anritsu MS2721B and MT8222A, which were configured to acquire data in 464 Mhz with a resolution bandwidth of 1 Mhz using the zero-span option. Then sweeps of 6 seconds were done and stored into variables of Matlab, along with some other information as the configuration of the spectrum analyzer and the time. The coordinates of the place were also stored thanks to the GPS antenna connected to one of the spectrum analyzers. Also, a signal generator was generating a squared signal of 1 Hz which was an input to both spectrum analyzers to operate as a trigger so the data from the spectrum analyzers was acquired simultaneously.

The procedure was the following: we placed the antennas with the minimum spacing and started to drive forward. Then we started the acquisition of data, and stopped the car when all the data was taken. After that we drove backwards to the starting point, increased the space between the antennas, and started again.

7.2 Measurements processing

Once the measurements were taken, next step was the data processing. First graphic to calculate is the the envelope correlation of signals as a function of the space between antennas, which is shown at figure 7.4.

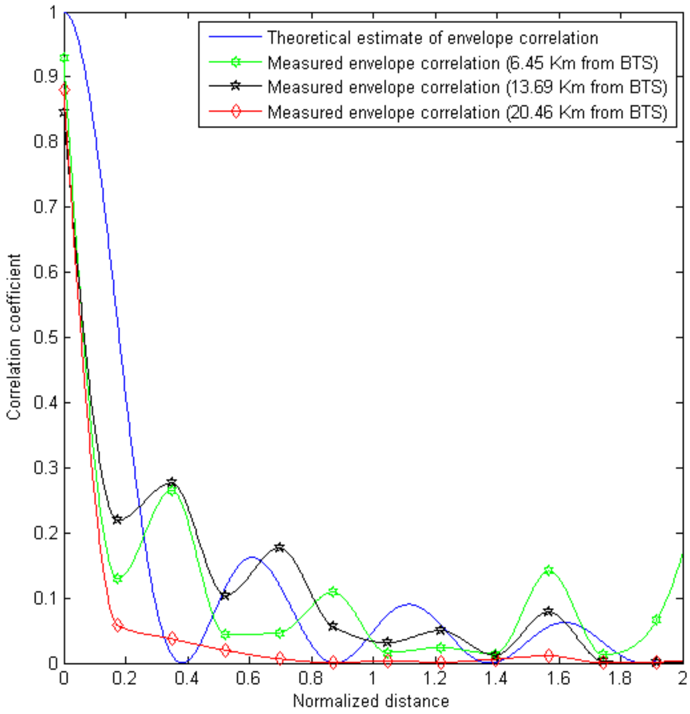

Figure 7.4 - Envelope correlation for measurements

We can notice that the correlation envelope does not fit exactly with its theoretical shape. This behaviour was predictable, as stated in point 4, that shape is for two omnidirectional antennas, and even though the antennas are intended to be omnidirectional, they cannot be perfectly. Also, they were mounted on the roof of the car, which would modify their radiation patterns, and finally, the most important effect for small spacings, is the mutual coupling between antennas, which also modifies the antenna pattern.

But still can be observed a resemblance to the theoretical envelope, which is a Bessel function. It is mainly observed at the closest measurement to the BTS, and can be also noticed in the second measurement, but the third one, which was taken at 20.46 Km from the BTS does not have a resemblance to the theoretical one.

As for the diversity gain, at next figure we can see how much gain it was achieved in function of the separation of antennas, and the correlation coefficient to compare both.

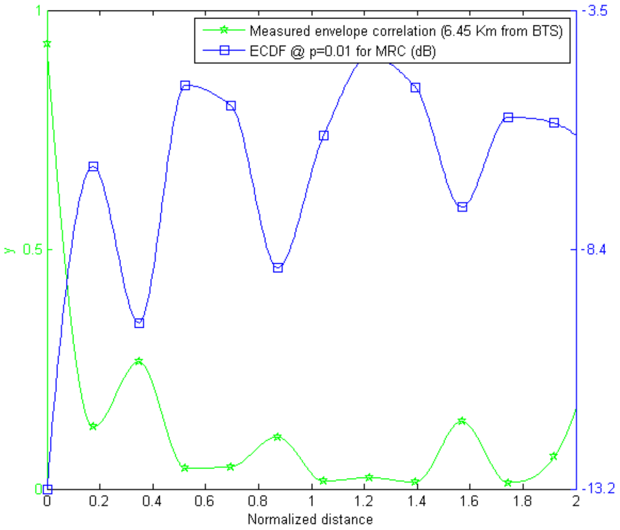

Figure 7.5 - Correlation and MRC

We can conclude that the correlation coefficient is low enough for achieving a good signal at a spacing of 0.2 wavelengths, and it is possible to have a better signal when increasing the spacing between antennas to around 0.6 and 1.2 wavelengths.

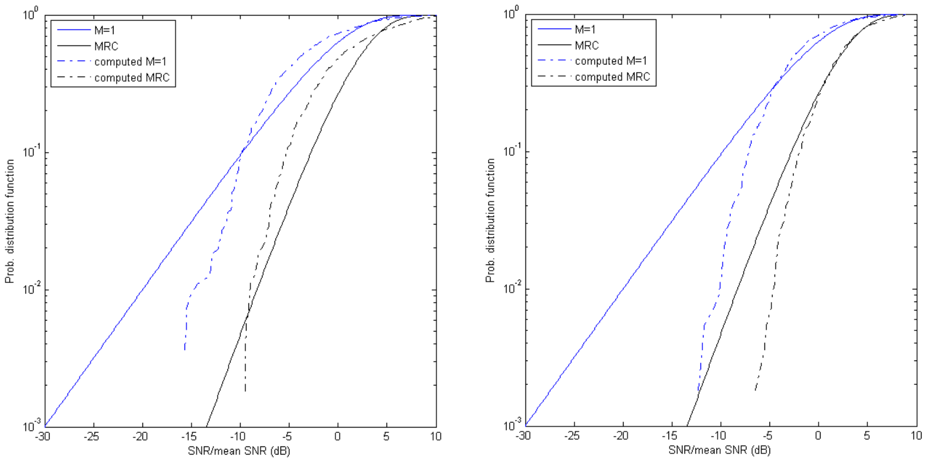

Figure 7.6 - Div. gain for 0.9 and 1.2 wavelenghts

At figure 7.6 is possible to see the diversity gain for an antenna separation of 0.9 wavelengths, where the correlation is high, and at 1.2 wavelengths, where the correlation is low.

As we can see for a higher separation the diversity gain achieved using MRC is slightly higher. Now it is presented some graphics comparing the histogram of the signals used to compute the diversity gain, and the theoretical ones.

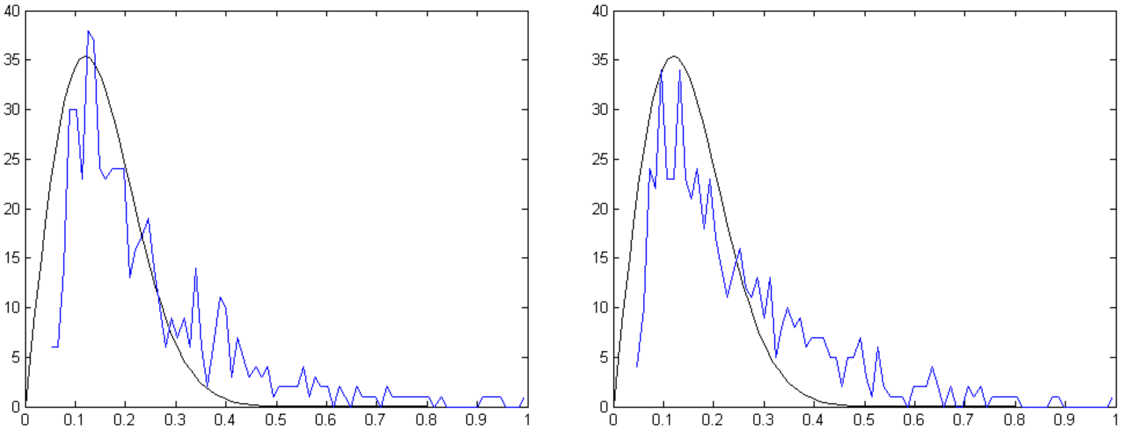

Figure 7.7 - Histogram of the measurements

At that figure it is shown that our distributions resembles to a Rayleigh distribution, but they are not exactly equal. This is due to the fact that even though there was no line-of-sight, the received signal travelling in a straight line was surely stronger than the reflected or diffracted signals.

8. Conclusion and future work

In this thesis the plausibility of implementing receive antenna diversity in a CDMA450 system has been evaluated theoretically and empirically. Two different methods of diversity have been considered; polarization and space diversity, both of them using only two antennas. Among all the diversity combining methods, we focused on the one which provides higher gain, the MRC.

Simulations were performed to calculate how much diversity gain it is possible to achieve in a spread signal of 1.25 MHz, which is used in the EV-DO standard, and the diversity gain for the no-spread signal of 100 KHz. It is remarkable the higher gains for the spread signals, especially for higher time delays. And the results shows that one percent of the time it could be possible to have around 11 dB of gain, and ten percent of the time, around 7 dB of gain.

Some measurements were taken on the environment where the diversity would be implemented, in the forest, where the electromagnetic interference produced by the heavy machinery cutting trees could be measured. At the band of interest, a noise of around 5 dB was measured.

Finally, we were able to take diversity measurements in the forest for two antennas with different spacings. The results show that the separation needed for an effective diversity at the receiver is much smaller than the needed in transmission. Also, it is noticeable that the correlation coefficient between both signals is different than the theoretical one, due to the fact that the radiation pattern of the antennas is not omnidirectional because of the mutual coupling and other effects.

We can conclude that a good space between antennas for achieving a good diversity gain is 0.6 wavelengths, which is 40 cm.

About the measurements, there are some points that would be interesting to examine; it would be interesting to have measurements with polarization diversity, so it would be possible to compare the results with space diversity and find out the separation at which the polarization diversity gives the same gain. Also it would be interesting to have measurements at more points and with smaller spacings so we could see a better shape of the correlation envelope.

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