M.I.M.O Channel Model for High Capacity Wireless Networks and Simulator for Performance Analysis

Bachelor thesis performed in Electronics Systems

by

Javier Alonso Valdesueiro

LiTH-ISY-EX--06/3882--SE

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Supervisor: Kent Palmkvist
Examiner: Kent Palmkvist

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Institutionen för systemteknik
581 83 LINKÖPING

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Titel
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Författare
Author
Javier Alonso Valdesueiro

Sammanfattning
Abstract
The wireless communications have suffered, in these last years, one of the greater technological growth within the communications via radio. The application of multiple antennas, as much in transmission as in reception has taken to an impulse of the study of different models from propagation channels.

Taking this into consideration, the different types from mentioned models are going to be studied.

The work that the ISY department at the Institute of Technology of the Linköping University has proposed is to develop to a propagation channel model, with several antennas in reception and transmission, that one first approach allows a capacity of the channel study, in absence of measures of possible scenarios, as well as the development of a small simulator that allows to analyze its benefits.

Nyckelord
Keyword
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The wireless communications have suffered, in these last years, one of the greater technological growth within the communications via radio. The application of multiple antennas, as much in transmission as in reception has taken to an impulse of the study of different models from propagation channels.

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English

After many years of study, finally, I finish here in Sweden which began when I was young in a school of Madrid.

I would like, in these lines, to thank for all the people who have made this adventure possible. I will begin by my parents and my brother, whose continuous effort in doing a person to me of good I have had all the opportunities that the life has offered me. To Beatriz to be next to me, so far and so close, in this final straight line of the race, and all the friends from Madrid who have contributed to their patience and their friendship at the best moments of my life.

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Finally, I give thanks for this year of experiences, adventures, study and friendship. To remember that this he has been one of the best years of my life, not only by the place where there am been working, but by people that there am well-known here, European and Spanish.

Javier Alonso Valdesueiro

Linköping, Sweden

May, 2006

Spanish

Después de muchos años de estudio, finalmente, termino aquí en Suecia lo que empezó cuando era niño en un colegio de Madrid.

Me gustaría en estas líneas agradecer a todas las personas que han hecho posible esta aventura. Empezaré por mis padres y a mi hermano, a cuyo esfuerzo continuo en hacerme una persona de bien le debo todas las oportunidades que me ha brindado la vida. A Beatriz por estar junto a mí, tan lejos y tan cerca, en esta recta final de la carrera y todos los amigos de Madrid que han aportado su paciencia y su amistad a los mejores momentos de mi vida.

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Javier Alonso Valdesueiro

Linköping, Sweden

Mayo, 2006

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1. INTRODUCTION

1.1 MAIN GOAL

The main goal of this thesis work is to study the different types of existing models for simulation of propagation channels; that is, to understand in the situations which is necessary to use a type of model and to choose the most appropriate among the proposed ones for a preliminary study, as well as to develop with the Matlab/Simulink tool a simulator of the benefits of this model. Then, to study the capacity of a particular case, the development of a simulator of wireless network based on OFDM transmission described on 802.11a PHY layer standard will be made.

1.2 PLANNING

The following steps have been followed for developing this thesis work:

- First of all, a few papers related to each one of the models was looked for, read and understood to obtain enough knowledge about the topics, words and, in each case, to choose one of the models proposed in the bibliography.

- Secondly, to choose one model type within the possibilities of the thesis work; in this way, it has been thought that there were not measures available about propagation channels of indoor scenarios or buildings, and there were not measures about arrays antennas and their behaviour. This lead to make several considerations which will be explained later.

- Thirdly, once the considerations and the chosen model had been decided, the next task was how the channel capacity is obtained. In this case, the same paper which describes the model, describes the way to get these capacity.

- To finish the first part of this thesis work, it was necessary to develop a Matlab script which could obtain the propagation channel capacity in different situations.

- The second part of this thesis work was to develop a basic wireless network simulator. In this step, it was necessary to read the 802.11a PHY layer standard and understand how 802.11a

PHY layer simulator works. That simulator was found in internet with free access.

- Finally, a basic simulator was begun to be used with a BPSK modulation and with different transmission rates with the intention to find some real results. They will be presented later.

1.3 RESOURCES

The resources used to develop this thesis work have been the following:

1.3.1 Software

- MATLAB 7.0.1 (R14)
- Simulink
- Operating system: Windows XP Professional Edition

1.3.2 Hardware

- CPU, Intel centrino 1,5 GHz 10424MB RAM Memory

1.3.3 Internet

- http://ieeexplore.ieee.org
- www.liu.se
- www.uah.es
- www.mathworks.com/matlabcentral/fileexchange

2. INTRODUCTION TO MIMO CHANNELS

In this section an introduction to the basic concepts of channels MIMO will be exposed. Channel capacity, the channel decomposition and the characteristics of the channels according to their capacity will be described next.

2.1 MULTIPLE-INPUT-MULTIPLE-OUTPUT CHANNELS

The model used in MIMO channels is:

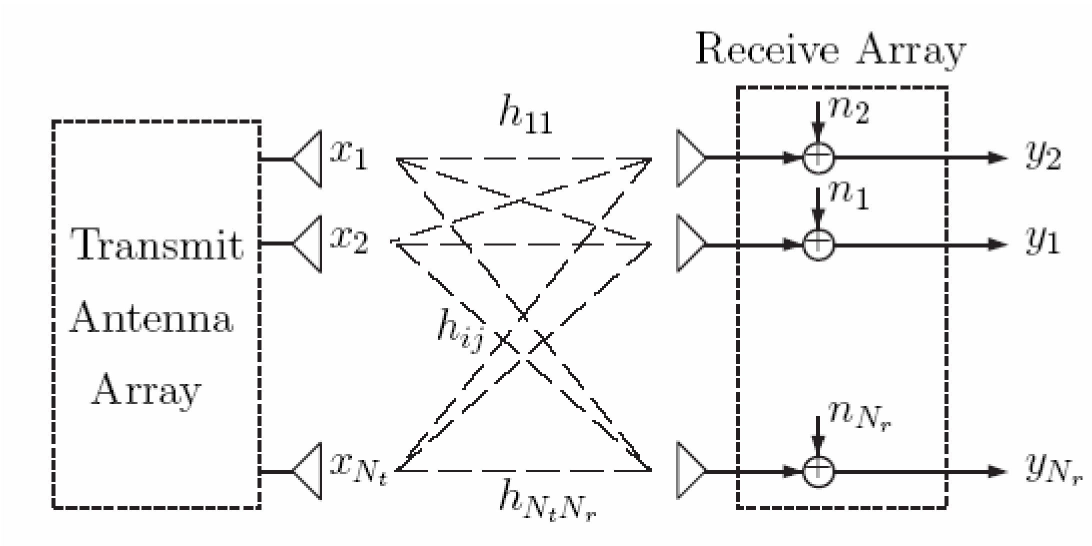

Figure 1. MIMO channel model.

As is seen in [21] this is the used model to describe the correlated parallel channels or MIMO channels. This kind of models is described by the matrix equation following:

$$y = Hx + n$$

where, as is seen in [21]:

Xn are the transmitted complex signals, as the channel gains h_{ij} and the received signal y_n are.

n is complex additive Gaussian noise with variance N_0 (that is $N_0/2$ in each dimension).

h_{ij} are complex gain coefficients modelling a random phase shift and a channel gain.

In the case of study, MIMO Rayleigh channels will be considered because they are often used to model a scattering-rich (like wireless environment) or mobile radio transmission environment.

2.2 SINGULAR VALUED DECOMPOSITION (SVD)

As is seen in [21], the matrix **H** can be decomposed by SVD method.

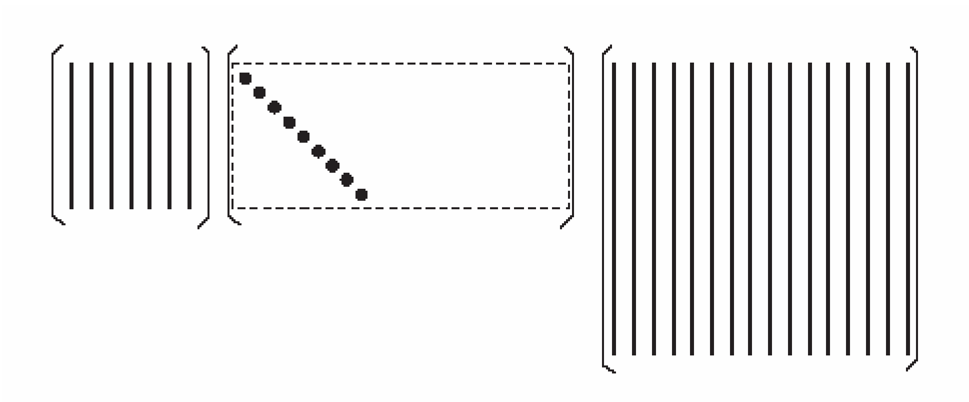

Figure 2. SVD

$$H = UDV^H$$

where

U and V are the unitary matrices, i.e., $UU^H = I$ and $VV^H = I$;

D is the singular values of **H**, which are the (positive) square roots of the eigenvalues of $\mathbf{HH^H}$ and $\mathbf{H^HH}$.

Now, the channel equation can be written in an equivalent form:

$$U^H y = \tilde{y} = DV^H x + n$$

This leads to parallel Gaussian channels, as is seen in the next figure:

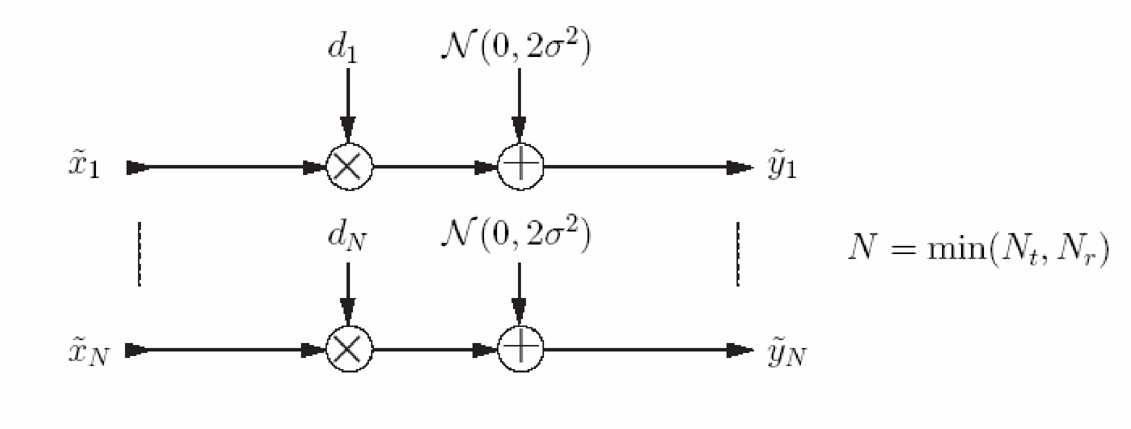

Figure 3. Parallel Gaussian channels

This can be expressed as:

$$\tilde{y}_n = d_n \tilde{x}_n + \tilde{n}_n$$

2.3 MIMO FADING CHANNELS

Following the [21] indications of talking about MIMO fading channels, the expression of the capacity can be written as:

$$C = E_H \left[\log \det \left(I_{N_r} + \frac{E}{2N_t\sigma^2} HH^H \right) \right]$$

By the law of large numbers, it can be said:

1. $HH^H \overset{N_t \to \infty}{\rightarrow} N_t I_r$ and $C = N_r \log \left(1 + \frac{E}{2\sigma^2} \right)$
2. $H^H H \overset{N_r \to \infty}{\rightarrow} N_r I_t$ and $C = N_t \log \left(1 + \frac{N_r}{N_t} \frac{E}{2\sigma^2} \right)$

In [21] the evaluation of capacity formula is explained in two pages, and different methods to make this evaluation can be seen.

2.4 CHARACTERISTICS OF MIMO CHANNEL

From the division seen in [21], there are four main characteristics in MIMO channels:

1. *Rank Classification [21].* MIMO channels can be classified as *high-rank* or *low-rank* channels. This classification is made based upon correlation properties of the receiver array response vector, or the singular values of the channel response matrix **H**.

2. *Orthogonal [21]*. Channel path gains present the upper limiting case for the MIMO channel capacity. In this case, the *non-zero* squared singular values of the channel response matrix **H** are given by:

$$d_n^2 = N_r E\left\{h_{nn}^H h_{nn}\right\}, i = 1,2,..., N_t$$

3. *Statistically independent [21].* Channel path gains h_{ij} are usually modelled as uncorrelated complex Gaussian random variables. In this case, the eigenvalues of $\mathbf{HH^H}$ for $N_t \geq N_r$ and $\mathbf{H^H H}$ for $N_t \leq N_r$ are given by *Wishart distribution*.

4. *Correlated channel path gains [21].* Correlated channel path gains occur in real-world cases. The completely correlated case such as in *long-distance scatter-free wireless links* identifies the lower-capacity limit for MIMO channels. In this case, the *non-zero* squared singular values of the channel response matrix **H** are given by:

$$d_n^2 = N_r \sum_{n=1}^{N_t} E\left\{h_{nn}^H h_{nn}\right\} = N_r N_t$$

In [21], the high-rank and low-rank are described and their characteristics are explained. They are going to be refered here for their importance.

1. High-Rank [21]:

- High-Rank MIMO channels occur when there is little correlation among channel paths gains.
- MIMO channel have a diversity gain defined by the rank of $\mathbf{HH^H}$.
- The maximum achievable diversity gain is:

$$rank\left(HH^H\right) = \min\left(N_t, N_r\right)$$

- The orthogonal channel gain case represents the upper limit for the capacity of MIMO channels, and the maximum diversity gain.

2. Low-Rank [21]:

- Low- Rank MIMO channels occur when there is a strong correlation between the channel path gains.
- The correlation characteristics determine the rank of $\mathbf{HH^H}$, which in turn determines the diversity advantage.
- A completely correlated **H** matrix is a scaled version of all one's with dimensions $N_r \times N_t$ and provides no diversity gain over the single antenna case.

In both cases, [21] saw a reduced expression for their capacities. [21] has been used as a reference test in this thesis work, and it's used as a beginning point in the study.

3. INDOOR MIMO WIRELESS CHANNEL MODEL

3.1 INTRODUCTION

The last investigations in propagation radio have demonstrated that the theoretical capacity of wireless systems, operating in multipath environments and with multiple antennas, as much in reception as in transmission, are increased remarkably. In order to maximize the data throughput, this type of multiple-inputs multiple-outputs systems, take advantage of the structure of the channel transfer matrix (**H**) to be able a significant increase in comparison with the use of only a radiating element.
This is the reason, for which an extensive study of the different types of models is necessary, which are able to simulate the behaviour of the matrix H under different circumstances from transmission-reception and thus to be able to establish that strategies and architectures are most advisable in each case.
Several types of models within the bibliography exist. Most of them operate the contribution to the study of the multipath capacity of authors G. J. Foschini and M. J. Gans, as well as To A. Saleh and R. T. Valenzuela. Here, a preliminary list of them is presented:

- Analytical models. They have initially been employed in Foschini and Gans work with the attempt of having a preliminary vision of the MIMO channel capacity and behaviour. They have a simple computing but they often don’t represent the real behaviour of channels [1]-[3].

- Direct measurement models. They provide a certainly characterization of **H** since a statistical generalization from the data collected in the measures is derived. They have the problem to serve, only, in the situations in which the measures have been made. Certain configurations and concrete scenes present/display unforeseeable behaviours for other circumstances. This makes hard its generalized use [4]-[8].

- Deterministic physical models. This type of models obtains a precise statistical representation of a certain scene configuration, sacrificing in the way the computational load, which is increased substantially. One example of this kind of model is the ray tracing model [9],[10].

- Physically based statistical models. They can obtain an accurate channel behaviour based on statistical models, fitting the models to the measured data. They allow to study different types of configurations of antennas and scenes of propagation and require little computational load [11]-[14]

In this thesis work a preliminary presentation of a physically based statistical model, previously presented/displayed will be made in the end to present/display the model implemented with MATLAB.

3.2 PHYSICALLY BASED STATISTICAL MODEL

In the bibliography [11]-[13], two examples of physically based statistical models can be found as a bases for the later studies of MIMO systems, which characterize channels multipath but non MIMO systems. In addition a third paper which presents/displays one first approach to the characterization of channels MIMO is added [14]. It is the last paper which will be described in this section, in this way, to have a general vision of how this type of models work and thus to be able to understand the different solutions adopted in the development from the final model.

3.2.1 Preliminary assumptions

Some preliminary considerations exist, before exposing the model proposed in [14] that will place the reader within the framework precise to understand the reason why it has determined that this model is indicated to use as its bases. The works try to model a wide band indoor MIMO wireless model, and this has the next consequences:

1. A wide band wireless channel is described with the following expression:

$$y(\tau) = H(\tau) * s(\tau) + n(\tau)$$

where $s(\tau)$ is the transmitted signal, $y(\tau)$ is the received signal, $n(\tau)$ is an AWGN, * denotes convolution and τ is de delay variable. In this case, the channel will have temporary taps or different moments of arrival, due to its multipath behaviour. This means, that it will be frequency selective.

2. Due to the fact that the channel is indoor defined, it will be assumed that the receiver doesn't suffer significant temporary variations in its position. That means, there isn't a temporary fading in the channel.

3. In the model proposed in [1] the authors divide the propagation in clusters and inside the clusters in rays. Under the assumptions done in [14] it can be said, there is a cluster covariance matrix which allows achieving the $H(\tau)$ matrix, and which is related with the array of reception-transmission.

3.2.2 ***"A Generalized Space-Time Multiple-Input Multiple-Output (MIMO) Channel Model"*** [15]

In order to find a wide band model, it is necessary to find a generalized model which allows making simplifications over itself with the purpose of adapting it to the concrete necessities of the proposed work. This is the reason why R. Valenzuelas' paper is mentioned in this thesis work. In this paper a generalized model is seen. This is a good beginning for the next model proposed.

The model proposed in [15] is:

$$h_{n,m,q,s} = \sqrt{P_q(\tau_q)} \sum_{l=1}^{L} A_{l,q} \sqrt{P_q^{BM}(\phi_l^B, \phi_l^M)}$$
$$\times G_m^B(\phi_l^B) \exp\left\{ i \vec{k}_l^B \cdot \vec{d}_m^B \right\} G_n^M(\phi_l^B) \exp\left\{ i \vec{k}_l^M \cdot \vec{d}_{n,s}^M \right\}$$

where

- L is the number of wave components for each of the paths;
- P_q is the average power of the qth path given by the PDP (*Power Delay Profile*), i.e., relative power as a function of τ_q;
- P_q^{BM} is the average power per wave component determined by the joint PAS (*Power Azimuth Spectral*) at the base and mobile, i.e., relative power as a function of AOD (*Angel of Departure*) and AOA (*Angle of Arrival*);
- ϕ_l^B is the AOD at the base for the lth wave component;
- ϕ_l^M is the AOA at the mobile for the lth wave component;
- $A_{l,q}$ is a complex Gaussian random variable with zero mean and unit variance;
- G_m^B is the antenna pattern of the mth antenna at the base as a function of ϕ_l^B;
- G_n^M is the antenna pattern of the nth antenna at the mobile as a function of ϕ_l^M;
- $\vec{k}_l^M$ is the directional vector at the mobile with amplitude $2\pi/\lambda$ and direction of AOA of the lth component;

$\vec{k}_l^B$ is the directional vector at the base with amplitude 2π/λ and direction of AOD of the *l*th component;

$\vec{d}_m^B$ is the position vector of the *m*th antenna of the base station antenna array;

$\vec{d}_{n,s}^M$ is the position vector of the *n*th antenna of the mobile antenna array at time *s*;

The appearance of physical aspects as well as the statistics obtained from real measures can be observed in this model. The geometry of antenna arrays and their radiation pattern as well as the statistic obtained from the PAS and of the PDP takes part in the model. If the previous preliminary considerations are applied to this general model the following conclusions can be obtained:

1. The temporary dependency does not have to be taken into account in the case to study.

2. AOD statistics are assumed to follow the same distribution as AOA, which is reasonable for the indoor channel with the same basic configuration on transmitting and receiving [14]. In that case, the same considerations as in [14] can be done. The same results are obtained and the covariance matrix is:

$$R_{m1n1,m2n2} = \frac{1}{L}\sum_l |\beta_l|^2 L_{m1m2}^R\left(\Theta_l^R\right)L_{n1,n2}^T\left(\Theta_l^T\right)$$

where

$R_{m1n1,m2n2}$ is the average covariance matrix of **H**;

$|\beta_l|^2$ is the variance of average-ray power in each cluster taken as $CN(0,/\beta_l/^2)$;

$L_{q1q2}^P\left(\Theta_l^P\right)$ is the physical part of the model related with AOD/AOA pdf and the antenna array pattern (see [14], page 594, equation 20 and following).

For certain special cases, closed-form expression for $L_{q1q2}^{P}\left(\Theta_{l}^{P}\right)$ exist. For arbitrary antenna gain and angular ray distributions, however, $L_{q1q2}^{P}\left(\Theta_{l}^{P}\right)$ is computed numerically.

3.3 INDOOR MIMO CHANNEL MODEL DEVOLOPED

In this section the mathematical structure used by the developed model will be explained, as well as the structure of the used algorithms to obtain the results which will be shown afterwards.

3.3.1 Preliminary Considerations

As is in [17] and [18] is explained, an approach of a complex valued matrix **R** can be obtained by means of the Kronecker product of two complex valued matrices **X** and **Y** optimally. In that case, the channel covariance matrix for each cluster *l* can be written like:

$$R_{H}^{l} = R_{TX}^{l} \otimes R_{RX}^{l}$$

supposing that the statistics of receiver and transmitter are separated.

In the European research initiative COST 259 [19] a tapped delay line SISO channel model is proposed:

$$h(\tau) = \sum_{l=1}^{L} \sqrt{\bar{p}_l}\, g_l \delta\left[\tau - (l-1)\Delta\tau\right]$$

where

$\Delta\tau$ is the time spacing between following neighbouring taps, modelled as is seen in [11];

τ is the time delay;

g_l is a complex Gaussian random variable with zero mean and 1 variance;

$\bar{p}_l$ is the average power of the *l*th tap, define by:

$$\bar{p}_l = Ae^{-\frac{(l-1)\Delta\tau}{2\Gamma}}$$

where

Γ is the rms delay spread;

A is a normalization factor;

These two premises are necessary for the following formulation which implements the model proposed in this thesis work.

3.3.2 Proposed Model

The model proposed in this thesis work is the combination of the SISO channel model described before and to the Kronecker structure for each tap, described by:

$$H(\tau) = \sum_{l=1}^{L} \sqrt{\bar{p}_l} \left(R_{RX}^{l}\right)^{\frac{1}{2}} G_l \left(\left(R_{TX}^{l}\right)^{\frac{1}{2}}\right)^T \delta[\tau - (l-1)\Delta\tau]$$

where G_l are random matrices with i.i.d. CN(0,1) elements.
At this moment the covariance matrix is the last point in the proposed model to be defined.

3.3.3 Covariance matrices of transmitter and receiver

There is a low complexity algorithm to simulate the spatial covariance matrix for clustered MIMO channels [20] which is based on the following premises.

1. AOA and AOD have a Laplacian distribution with σ_φ standard deviation (RMS AS) of the PAS.
2. The antenna array is a uniform linear array (ULA).

Consequently, the covariance matrix for an antenna array has the following expression which has been obtained from [20]:

$$R(\phi_0, \sigma_\phi) \approx \left[a(\phi_0) \cdot a^H(\phi_0)\right] \circ B(\phi_0, \sigma_\phi)$$

where

ϕ_0 is the mean of AOA of the channel tap and it will be considered normal distributed inside [0,2π];

σ_ϕ is the standard deviation of the PAS (RMS AS);

$a(\phi_0)$ is the ULA array response vector given by:

$$a(\phi_0) = \left[1 e^{jD\sin\phi_0} \ldots\ldots\ldots\ldots e^{jD(M-1)\sin\phi_0}\right]^T$$

$$D = \frac{2\pi d}{\lambda}$$

and B is given by:

$$\left[B(\phi_0, \sigma_\phi)\right]_{m,n} = \frac{1}{1 + \frac{\sigma_\phi^2}{2} \cdot \left[D(m-n)\cos\phi_0\right]^2}$$

where *d* is distance between radiant elements in wave length and *m* and *n* are the index of the covariance matrix. As it can be seen in [20], this is the result for an especial configuration of $L_{q1q2}^{P}\left(\Theta_l^P\right)$, in another case it should be resolved numerically.

3.4 PROPOSED ALGORITHM

In the following section, the method of calculation of the channel capacity is used according to how the model of the developed channel is described. The used method to obtain pdf curves is also described, along with the used algorithm, as well as the use of script.

3.4.1 Wide-Band Channel Capacity

As is seen in [16], a wide-band MIMO system with M transmit elements and N receive elements supposing that the transmitted power is equally allocated to each transmit element and frequency sub channels, it can express its capacity like:

$$C = \int_W \log_2 \det\left(I_N + \frac{\rho}{M} H(f) H^H(f)\right) df \text{ bits/s}$$

where

W is the overall bandwidth of the MIMO channel;

H(f) is the normalized frequency response matrix for each narrow-band sub channel.

P is the average SNR at each receiver branch over the entire bandwidth;

The frequency response of each narrow-band sub channel is normalized using a common factor such that:

$$\int_W E\left(\|H(f)\|_F^2\right)df = WNM$$

3.4.2 MonteCarlo Simulations

In order to obtain the capacity pdf curves the MonteCarlo has been used. With this reason, a reiteration of the tests is made until it reaches an error level in the certain probability. The error evaluation is made with the following expression:

$$\varepsilon = \sqrt{\frac{1-P}{MP}}$$

where
M is the number of test used in the simulation;

3.4.3 Used Script

Script used is in charge of calling three functions which allow obtaining the probabilities that, a channel with a determined characteristic has one determined capacity. These functions are:

1. covarianzaEspacial This function is in charge of building the space covariance matrices of transmitting and receiving antennas array.
2. canal. This function is in charge of building de channel matrix **H** and the frequency response of this matrix.
3. monteCarlo. This function calls to canal at each test and gets its capacity.

The parameters used in this last function are:

K	is the number of test in MonteCarlo simulation.
B	is the channel bandwidth.
SNR	is the SNR at each receiver branch.
A	is the propagation attenuation factor.
L	is the number of cluster considered.
dE	is the delay excess considered at each channel.
dS	is the RMS delay spread considered at each channel.
M	is the number of transmit elements.
N	is the number of the receive elements.
d	is the distance between radiant elements.
RMSAS	is the RMS angel spread for Laplacian PAS.

The resulting vectors are:

p are the probabilities associated to a certain vector of capacities.
e are the errors associated to each obtained probability.

3.5 OBTAEINED RESULTS

3.5.1 Considered environments

For the analysis developed model profits the following situations have been considered:

1. 2x2 and 3x3 antennas setup.
2. Power is equally allocated at each receiver element and the SNR at each receiver branch is 20 dB.
3. 20 MHz and 120 MHz channel bandwidth have been supposed.

3.5.2 Obtained pdf curves

The results are shown in the following curves:

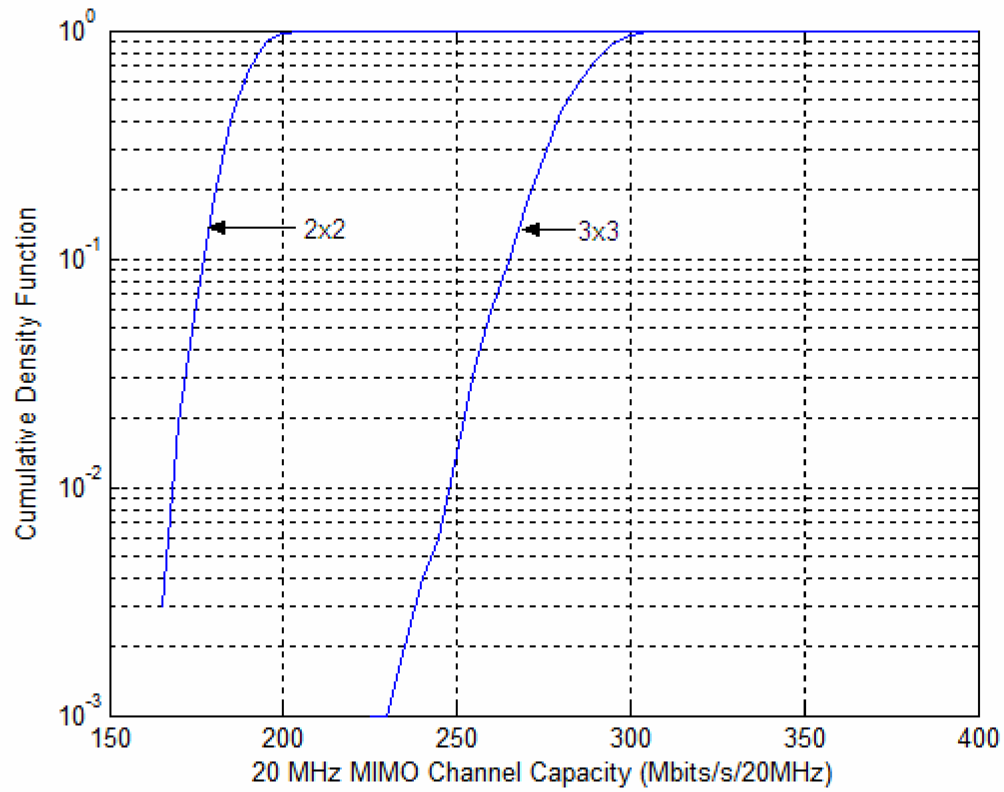

Figure 4. Obtained results.

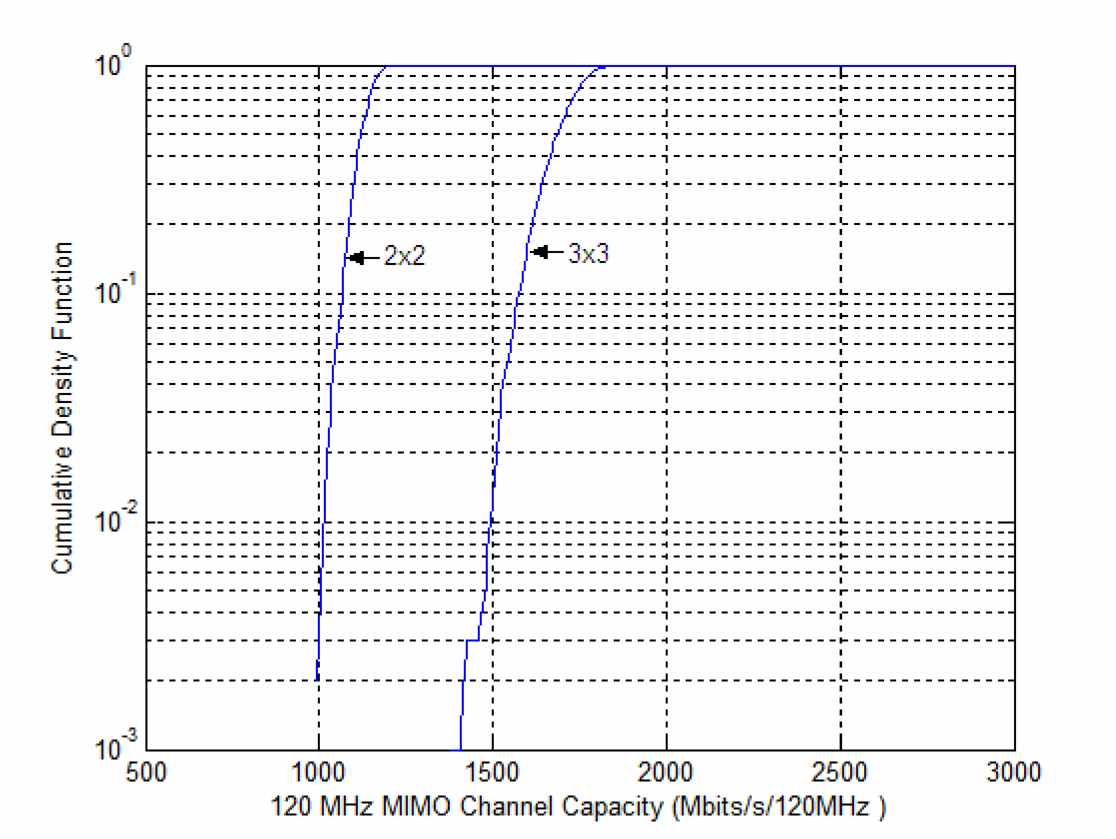

Figure 5. Obtained results.

In these figures, a diversity gain can be observed. In the 20 MHz channel a capacity of 177 Mbits/s/20MHz is obtained with a probability of 10%. In the 120 MHz channel a capacity of 1065 Mbits/s/120MHz is obtained. A diversity gain is observed for the 2x2 antennas setup and in 3x3 setup also.

4 DEVELOPED SIMULATOR

4.1 NECESSITY OF THE SIMULATOR

In this section, the reason of the development of the simulator will be explained in detail. The necessities of the department in which the works have been developed, have been considered at the time of finalizing the same one. Within these necessities, the study of different standards from wireless technology is included. After the development of simulators based on standard IEEE 802.11a the application of MIMO technology to these simulators was necessary. To the light of the development of the standard IEEE 802.11n, which is being carried out at the moment, the development of a basic simulator is necessary to have a tool which allows testing the different proposals from standard saying.

With this introduction, the necessities of the department are shaped in the following objectives:

- The simulator must allow the inclusion of the different blocks that appear in the new standard IEEE 802.11n.

- Standard IEEE 802,11, from its version 802.11a describes the transmission based upon OFDM technology. For this reason, OFDM transmission must be contemplated in the simulator.

4.2 CHARACTERISTIC OF THE DEVELOPED SIMULATOR

The characteristics of the developed simulator are described below:

- The simulator has been completely developed by SIMULINK. It allows including any kind of new developed block by the department, as well as watching the behaviour of the system in real time.

- The simulator contemplates the OFDM transmission through the technology developed in [22] and the channel equivalent for this type of transmissions, which will be described in the following section.

- The simulator allows fitting the speed of transmission, as well as the SNR by reception branch and the number of tests to obtain the BER of transmission.

- The simulator makes the number of wanted tests, according to the MonteCarlo simulations and with different observations from the channel to study. It allows finding the BER with a desired error.

- The simulator has an Alamouti decoding architecture at the receiver. Many different decoding architectures with their features exist. They will be explained in the following sections.

The resulted simulator is shown in the next figure

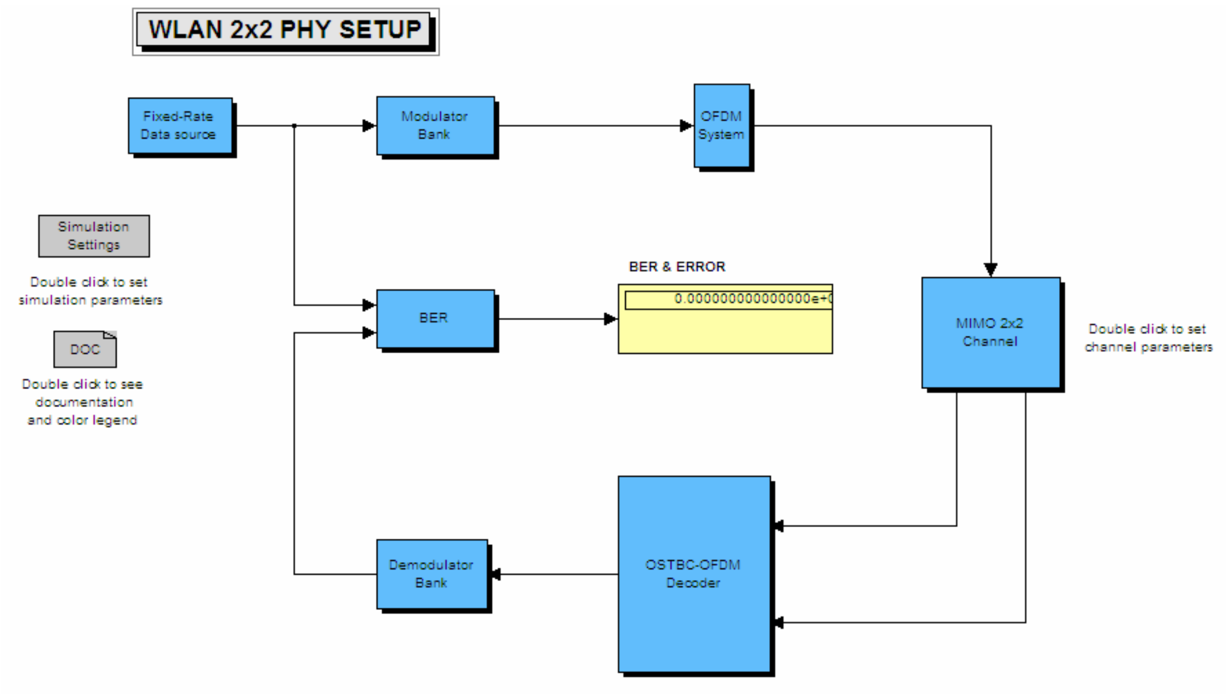

Figure 6. Developed simulator

4.3 RESPONSE CHANNEL MATRIX, H AND ITS OFDM EQUIVALENT

As is shown in [23], the structure of the physical layer for a radio network has the following structure in the transmitter and the receiver:

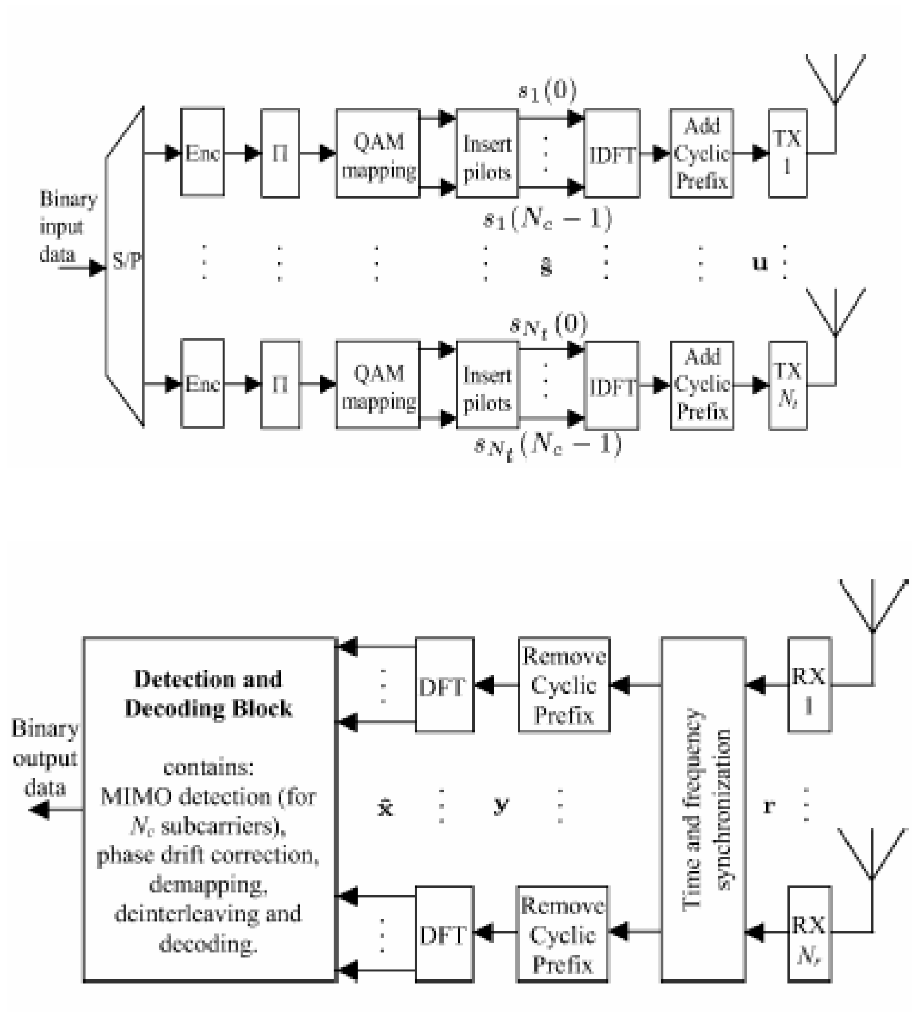

Figure 7. OFDM MIMO transmitter and receiver.

where

1. Nc is the number of the sub-carriers used in the OFDM transmission.
2. In the case of the developed simulator the channel codification, the interleaving and the QAM mapping, are replaced by a simple BPSK modulator.

In [23] explains the model to use in case of transmission OFDM, or as a response channel matrix H is transformed into the OFDM transmission. Following the results described in [23], the following matrix is obtained:

$$\hat{\mathbf{H}} = \begin{pmatrix} \mathbf{H}(0) & & 0 \\ & \ddots & \\ 0 & & \mathbf{H}(N_c - 1) \end{pmatrix}$$

where the *i*th block diagonal element is the $N_r \times N_t$ MIMO channel of the *i*th sub-carrier and can be shown :

$$H(i) = \sum_{l=1}^{L} G(l) \exp\left(-j2\pi \frac{il}{N_c}\right)$$

Cyclic prefix with greater length than the number of echoes of the multi-path signal for ISI suppression and the channel is non frequency selective for each sub-carrier are supposed. So, for this sub-carrier, it may be written:

$$x(i,a) = H(i)s(i,a) + n(i,a)$$

where

a is the OFDM symbol in a certain moment;
i is the sub-carrier in a certain process moment;

Now an expression for $\bar{x}$ and the DFT process can be ignored in the simulator and added in the physical implementation of the system. If the MIMO channel model explained below is used the G(l) signal must be replaced by H(l). However, in this case, a non frequency selective channel for each sub-carrier can not be supposed and channel equalization must be added before de decoding architecture. This last consideration implies channel state information (CSI) at the receiver which is contemplated in the decoding architectures.

4.4 ENCODING/DECODING ARCHITECTURES

In [24], a preliminary division of encoding/decoding techniques is shown. In this paper two general techniques are described:

4.4.1 Orthogonal Space-Time Block Codes (OSTBC's)

The basic characteristics of these techniques are:

1. Total diversity;
2. Smaller transmission Rates;
3. Easy decoding

An orthogonal space-time code must fulfil:

$$C_k^H C_l = \begin{cases} I, & k = l \\ -C_l^H & k \neq l \end{cases}$$

In the Alamouti's code and in a 2x2 setup the expression of de coded signal in two consecutive slots is:

$$S = \mathrm{Re}(S_1)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \mathrm{Re}(S_2)\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} + \mathrm{Im}(S_1)\begin{pmatrix} j & 0 \\ 0 & -j \end{pmatrix} + \mathrm{Im}(S_2)\begin{pmatrix} 0 & j \\ j & 0 \end{pmatrix}$$

$$Slot1 = \begin{cases} antenna1 = S_1 \\ antenna2 = S_2 \end{cases} \qquad Slot2 = \begin{cases} antenna1 = -S_2^* \\ antenna2 = S_1^* \end{cases}$$

As is shown in [24], if a 2x2 setup is applied a matrix expression appears:

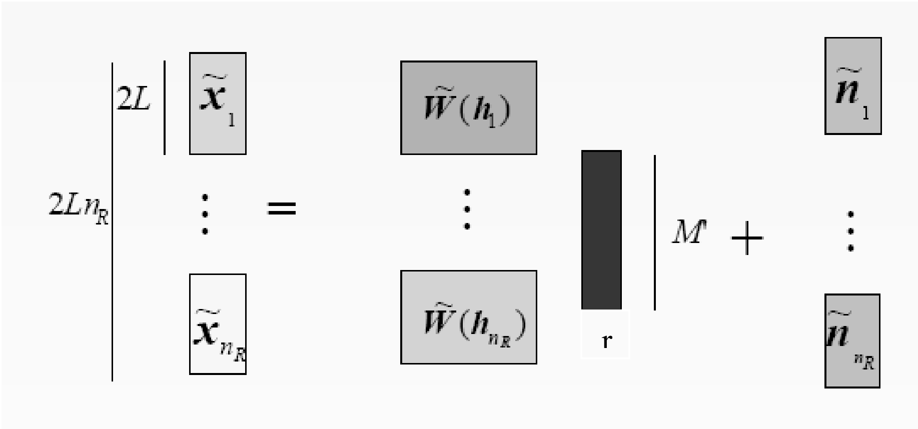

Figure 8. Matrix structure.

$$\tilde{x} = \tilde{W}(H)r + \tilde{n}$$

where

$\tilde{W}(H)$ are the combined codes of each symbol with correspondent channel response.

If the codes are orthogonal and known in the receiver the optimal detector it is obtained as:

$$\tilde{W}^T(H)\tilde{W}(H) = \|H\|^2 I$$

and

$$\hat{r} = Q\left(\frac{\tilde{W}(H)\tilde{x}}{\|H\|^2}\right)$$

where

$\hat{r}$ is the recovered signal;

$Q(x)$ is the selection of the nearest symbol in the transmitted constellation;

This means that the only thing needed is a match filter at the receiver.

4.4.2 Spatial Multiplexing (V-BLAST)

Te basic principle is to transmit a different signal by each transmitter branch as is shown in the next figure

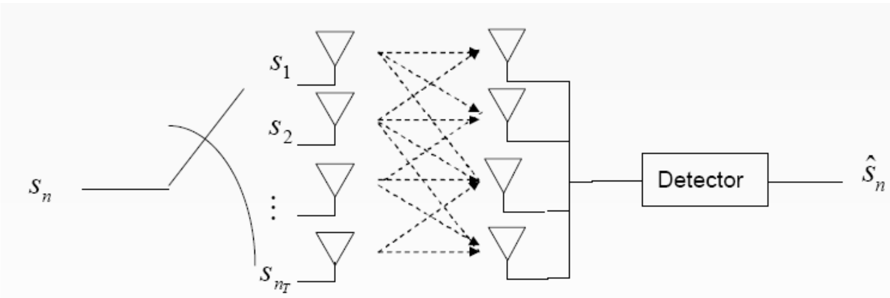

Figure 9. V-BLAST concept.

This architecture presents the following characteristics:

1. Less spatial diversity than the other technique.
2. Greater transmission rates.
3. Each signal can be coded independently or separately with the purpose of reaching the maxima capacity.

There are several techniques in order to establish the optimal detector. An example of these techniques is the following list:

1. Sphere Decoding.
2. MMSE Estimator + Hard Decision.
3. MMSE + Null & Cancelling.

In [24], all of the components of this list are described in detail, as well as in [25], where a complexity of reduced algorithms are proposed, due to a sphere decoding produce a cubic solution in relation with the problem to be solved.

4.5 FINAL RESULTS

The final simulator has offered preliminaries results in order to find the BER for a BPSK modulation, a 54Mbits/s transmission rate and different SNR at each receiver branch values.

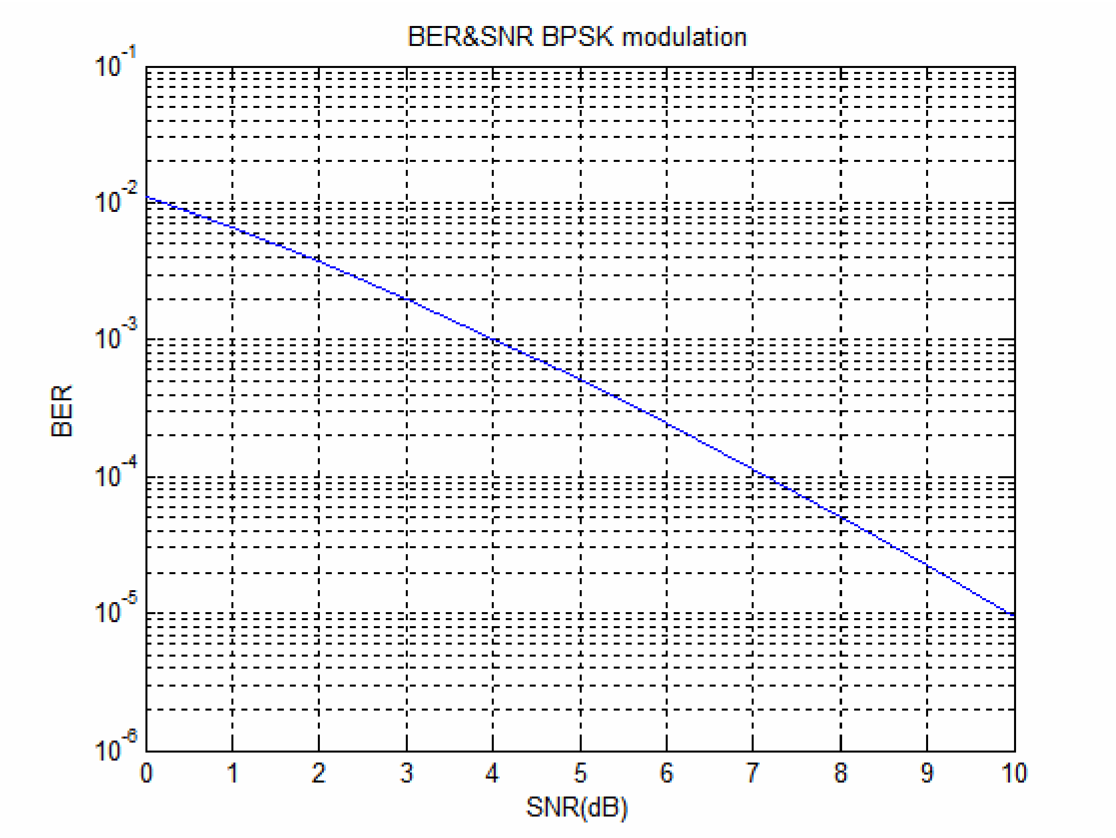

Figure 10. Simulator results.

This curve was obtained with a MonteCarlo simulation over a 50000 observations and tests. For this simulation a non-frequency selective channel was used because a frequency selective channel needs V-BLAST architecture in order to obtain good results. The V-BLAST architecture development can be a future work to add in the simulator.

5 FINAL CONCLUSION AND FUTURE WORK

In this thesis work a study of different kinds of MIMO channel models have been shown as well as small briefing of the different detection techniques for the MIMO environments. It should be a good beginning for the established work in the ISY department in order to obtain its own wireless system.

The future work can be divided in several steps, which have been discovered into the bibliography:

1. To develop a measure equipment to obtain different measures from different environments and setups. This measure equipment can be developed, as is shown in some papers, from the proposed bibliography.

2. To fix the proposed MIMO channel model with the measurements taken.

3. To include a frequency selective detection technique in the simulator and to include all the new techniques developed in the department.

4. To develop a physical system as it is shown in the proposed bibliography with the new techniques developed in the department.

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