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TYPICAL INDOOR CHANNEL MODELS AND THEIR INFLUENCE ON OFDM SIGNAL

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CONTENT

1. INTRODUCTION

In wireless communications, radio propagation refers to the behavior of radio waves when they are propagated from transmitter to receiver.
These radio waves are mainly affected by three different modes of physical phenomena: diffraction, reflection and scattering.

However, a unique important characteristic in a wireless channel is a phenomenon called fading which is simply the variation of the signal amplitude over time and frequency.

The aim of the thesis will be to give an overall idea of the different fading phenomena given in a wireless channel insisting on short-term fading in indoor areas where WLAN takes a role in.

The structure of the thesis will start with a brief introduction of the different modes of physical phenomena insisting on fading which affects radio waves.
As follows, physical layer characteristics and parameters in 802.11n standard within WLAN will be explained.

Second part will go deep into OFDM technique used in 802.11n, a technique used in order to avoid fading phenomenon explained in the first part of the thesis which makes wireless WLAN communications more resilient to interferences. ‘2-ray’, ‘exponential’ and “802.11” channel models will be introduced.

Finally, the thesis will conclude with Salah-Valenzuela (S-V) channel model, generating and testing the channel with Matlab and showing the most interesting statistical channel parameters.

2. RADIO WAVES PHYSICAL PHENOMENA

Radio waves are mainly affected by three different modes of physical phenomena:

Reflection: the physical phenomenon that occurs when a propagating electromagnetic wave impinges upon an object with very large dimensions compared to the wavelength. The signal is reflected by the object and it is reflected to its origin rather than being passed along the path to the receiver.

Diffraction: When the radio path between the transmitter and receiver is obstructed by a surface with sharp irregularities or small openings. It appears as a bending of waves around the small obstacles and spreading out of waves past small openings.
Its effects are generally most pronounced for waves whose wavelength is roughly comparable to the dimensions of the diffracting object or slit.

Finally, scattering: the physical phenomenon that forces the radiation of an electromagnetic wave to deviate from a straight path by one or more obstacles with small dimensions compared to the wavelength. Those obstacles that induce scattering such as foliage or for example lamp posts are referred to the scatters.

However, the propagation of a radio wave is a complicated and less predictable process that is governed by these three phenomena previously explained whose intensity varies with different environments at different instances that we can easily modify.

That is how it is introduced the phenomenon of fading.

As a difference with the previous three phenomena explained, fading is another source of signal degradation that is characterized as a non-additive signal disturbance in the wireless channel.

Fading may either be due to multipath propagation, referred to as multi-path fading, or to shadowing from obstacles that affect the propagation of a radio wave, referred to as shadow fading.

The presence of reflectors in the environment surrounding a transmitter and receiver create multiple paths that a transmitted signal can traverse. As a result, the receiver sees the superposition of multiple copies of the transmitted signal, each traversing a different path. [1]

Each signal copy will experience differences in attenuation, delay and phase shift while travelling from the source to the receiver. This can result in either constructive or destructive interference, amplifying or attenuating the signal power seen at the receiver with the possibility of appearing strong destructive interference which is frequently referred to as a deep fade and may result in temporary failure of communication due to a severe drop in the channel.

For this reason, it is interesting to take into account this phenomenon and analyze its properties in order to predict or to avoid this effect.

3. SISO CHANNELS FADING

The fading phenomenon can be broadly classified into two different types: large-term fading and short-term fading.

On the one hand, large-term fading occurs as the mobile moves through a large distance of the order of cell size. It is caused by path loss of signal as a function of distance and shadowing by large objects such as buildings, intervening terrains, hills and vegetation.

In other words, large-term fading is characterized by average path loss and shadowing which is just a slow fading process where the main signal is obscured and the amplitude and phase change imposed by the channel can be considered roughly constant over the period of use.

On the other hand, short-term fading refers to the rapid variation of signal levels due to the constructive and destructive interference of multiple signal paths when the mobile station moves short distances.

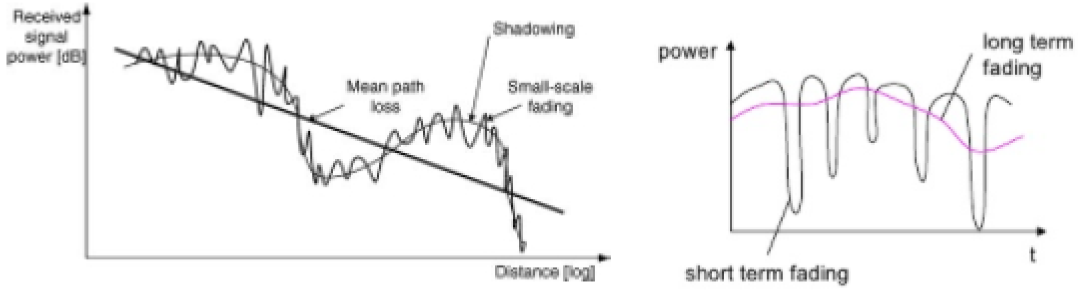


Fig.1. Short-term fading vs long-term fading [1]

In Fig.1 is illustrated the relationship between short-term fading and long-term fading.

Long-term fading is manifested by the mean path loss that decreases with distance and shadowing that varies along the mean path loss. The received signal strength may be different even at the same distance from a transmitter, due to the shadowing caused by obstacles in the path.

On the other hand, scattering components incur short-term fading which finally yields a short-term variation of the signal.

Short-term fading will be the aim of this first part of the thesis. As we could see in Fig.2 we will focus in small-scale fading part or short-term fading making a complete explanation of the terms "slow fading" and "fast fading" within multipath fading and “frequency–selective fading” and “flat fading” within time variance term.

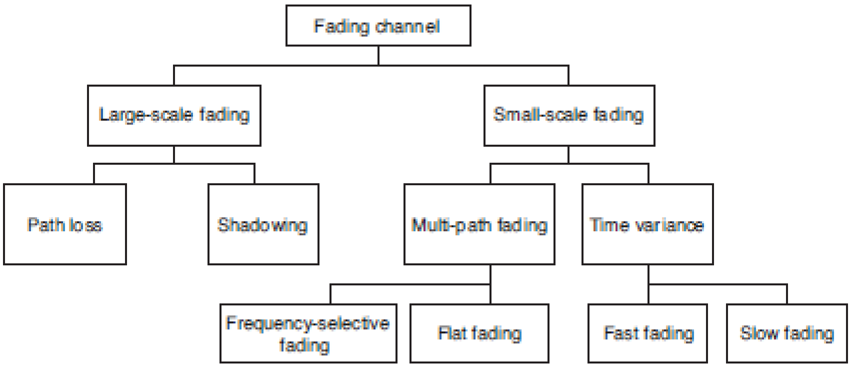


Fig.2. Classification of fading channels [1]

4. SHORT-TERM FADING

4.1 Factors influencing short-term fading

Short-term fading is referred to as fading in short. As previously introduced, short-term fading appears due to the effect of multiple signal paths, which cause interference when they arrive to the antenna with varying phases; constructive interference for the signals with the same phase and destructive interference for the signals with a different phase.

In other words, the variation of the received signal level depends on the relationships of the relative phases among the number of signals reflected from the local scatters. Furthermore, each of the multiple signals will reach the antenna at different speeds which will also produce changes in the signal level reception due to a delay in time.

Finally, another factor to take into account is the speed of surrounding objects. So, if objects in the radio channel are in motion, they induce a time varying Doppler shift on multipath components, thus, if these objects move at a greater rate than the mobile, then this effect dominates fading.

4.2. Parameters influencing short-term fading

Parameters and characteristics of a multipath fading channel within the short-term fading must be explained before starting to classify the different types of short-term fading.

Some of them are:

- Rms delay: Parameter interpreted as the difference between the time of arrival of the earliest significant multipath component (typically the line of sight component) and the time of arrival of the latest multipath components.

- Coherence Bandwidth: Used to measure the up-limit bandwidth that can be transmitted for a channel to be free of Intersymbol interference.

- Coherence time is the time duration over which the channel impulse response is considered to be not varying. Such channel variation is much more significant in wireless communications systems, due to Doppler effects.

- Delay Spread: the different paths between the transmitter and receiver correspond to different transmission times. For an identical pulse from the transmitter, multiple copies of the signals are received at the receiver at different moments. The signal of the shortest path(typically line of sight) reaches first than those on longer paths. The direct effect of these un-simultaneous arrivals of signal causes the spread of the original signal in time domain.

- Doppler Spread: Appears when a signal of a given frequency is transmitted in a medium with moving reflectors. The received signal has slight frequency variations from the original signal due to the interaction with those moving objects. This frequency variation at a given time is called spectral shift and the standard deviation of multiple spectral shifts is known as the Doppler spread.

It is caused by time selective fading. It means that for a particular instance of time, channel behaves as a fading channel and for rest it behaves as flat channel. [3]

4.3 Types of Short-Term fading

As Fig.2 shows, there are mainly four types of short-time fading. The type of fading will depend on the relation between the signal parameters (bandwidth, symbol period) and the channel parameters (rms delay and Doppler spread).

There are two types of fading based on multipath time delay spread and two types based on Doppler spread.

4.3.1 FADING BASED ON MULTIPATH TIME DELAY SPREAD

As we previously explained, delay spread causes inter symbol interference (ISI).

Fig.3 illustrates the characteristics of the different types of fading based on multipath time delay spread.

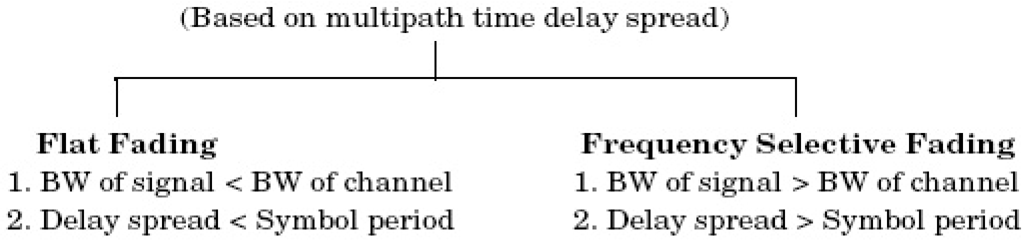


Fig.3 Flat Fading vs Frequency Selective Fading [3]

On the one hand, the wireless channel is said to be flat fading if it has constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal. In other words, flat fading occurs when the bandwidth of the transmitted signal is smaller than the coherence bandwidth of the channel.

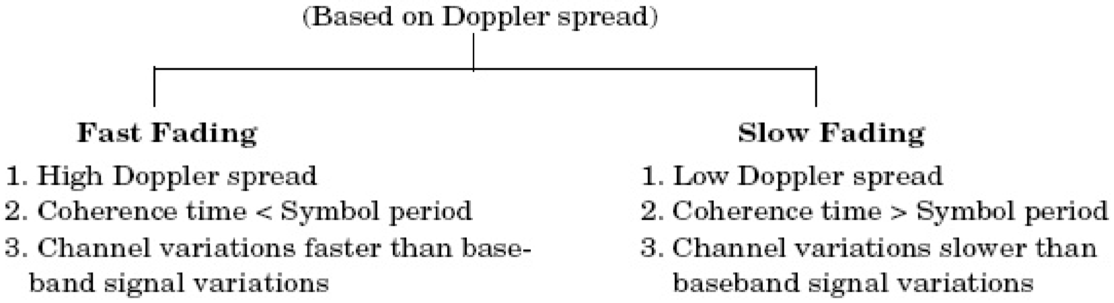
The effect of flat fading channel can be seen as a decrease of the Signal-to-Noise ratio and all frequency components of the signal will experience the same magnitude of fading.

On the other hand if the coherence bandwidth of the channel is smaller than the bandwidth of the signal, frequency selective fading appears, therefore, different frequency components of the signal experience uncorrelated fading.

Since different frequency components of the signal are affected independently, it is highly unlikely that all parts of the signal will be simultaneously affected by a deep fade as it can occur in flat fading.

4.3.2 FADING BASED ON DOPPLER SPREAD

Fig.4 illustrates the scheme for the different types of fading based on Doppler spread.



Fast Fading

1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than baseband signal variations

Slow Fading

1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

Fig.4 Fast fading vs slow fading [3]

On the one hand, in fast fading the coherence time is smaller than the symbol period, thus, a channel impulse response quickly varies within the symbol period.

On the other hand, slow fading consider the case where the channel impulse response varies slowly as compared to variation in the transmitted signal. . In this case, the channel does not change over the duration of one or more symbols, thus, it works as a static channel.

5. WLAN 802.11.

WLAN (Wireless Local Area Network), currently used in our homes, is a wireless distribution method that use high-frequency radio waves and allows users to move around the coverage area , often a home or small office , while maintaining a network connection to Internet.

The aim of this section will be to explain one of the most used standards within WLAN best known as 802.11n and most used in our currently devices. The structure of this section will be to give detailed information about the physical layer of this standard understanding how digital data is sent from one device to another using 802.11n.

With this information, we will be able to understand how the signal is propagated from the transmitter to the receiver and how fading and which types of fading are affecting this type of indoor communication.

Finally in this chapter we will discuss the various techniques and methods used to get digital computer data from one device to another using spread-spectrum and other physical layer modulation technologies being of our interest OFDM technique and MIMO technology.

5.1. Spread Spectrum Technologies (FHHS & DSSS)

Two types of spread-spectrum technology were first specified in IEEE 802.11 wireless LAN standard. What spread-spectrum technologies do is to take the digital information generated by a computer and, through the use of modulation technologies, send it across the air using radio frequency (RF).

We will make a brief introduction with the first spread spectrum technologies that appeared in the early standards of 802.11. As follows, a detailed explanation of OFDM spread spectrum technology used in 802.11n will be given in the next section.

On the one hand, FHSS (Frequency hopping spread spectrum) is one of the first spread spectrum technologies which operates by sending small amounts of information such as digital data across the entire 2.4 GHz ISM band. This technology changes the frequency in a specific hopping pattern and remains on the same frequency for a specified amount of time.

On the other hand, DSSS (Direct Sequence spread spectrum) operates using special techniques to transmit digital data modifying the radio frequency characteristics such as phase, amplitude and frequency.

Furthermore, in addition to a modulation improvement, DSSS uses technology known as a spreading code to provide redundancy of the digital data and helping the receiver detect transmission errors due to interference and making this technique resilient to interference. [4].

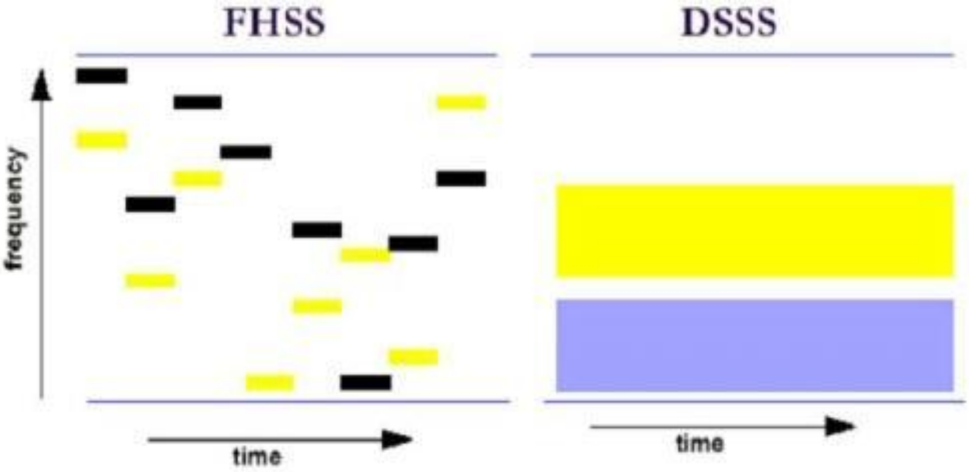


Fig.5. Spread Spectrum comparison in time FHSS vs DSSS [4]

As Fig.5 shows, FHHS uses different frequencies following a hopping pattern and DSSS only uses one frequency in the channel for the whole transmission.

5.2. 802.11n Physical Layer

The Physical Layer defines the electrical and physical specifications for devices. In particular, it defines the relationship between a device and a transmission medium.

As explained before, first versions of 802.11 such as 802.11b and 802.11g used spread spectrum technologies as FHHS and DSSS.

With the release of 802.11n, not only OFDM appears as a greater spread spectrum technology in order to make transmissions more resilient to interferences, but also MIMO antenna technology appeared to reduce multipath interference effect in WLAN transmissions.

Furthermore, ‘Channel Bonding’ best known as 40 MHz or interface network union is the second technology added to the 802.11n standard which can use two non-overlapping 20 MHz channels separately to transmit data simultaneously.

5.3 Channel Allocations

The 802.11b, 802.11g, and the low-frequency part of the 802.11n standards utilize the 2.400 – 2.500 GHz spectrum located in the ISM band.

802.11n standard utilize the 2.400 – 2.500 GHz spectrum located in the ISM band and also is the first also compatible with 5.725 – 5.875 GHz spectrum.

Each of these spectrums are sub-divided into channels with a center frequency and bandwidth. Depend on the frequency used (2.4GHz or 5GHz), the information will be spread by channels or ‘sub-frequencies’ in different ways.

5.3.1 2.4 GHz BAND

The 2.4 GHz band is divided into 14 channels, each one of 22 MHz size and spaced 5 MHz apart, beginning with channel 1 which is centered on 2.412 GHz.

It means that 2.4 GHz band goes from 2.402 GHz to 2.494 GHz if we take into account channel 14(not used by every countries) and it also means it is possible to find a maximum of three non-overlapping channels as for example(1,6 and 11) or (2,7 and 12)

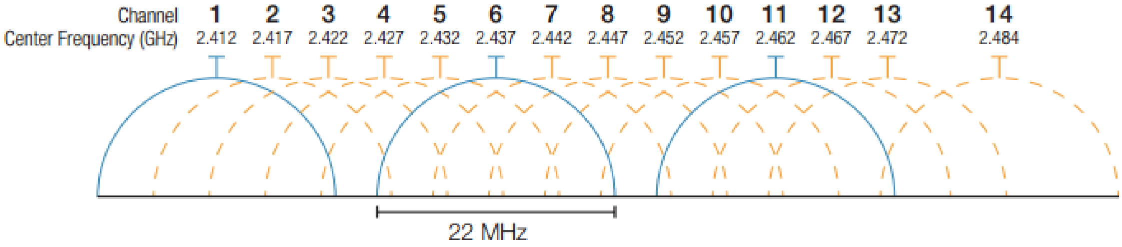


Fig.6. 2.4GHz band channels [6]

802.11n as we previously said can use two non-overlapping 20 MHz channels separately to transmit data simultaneously. It means that the channel can be 40MHz width and using 2.4 GHz band is possible to achieve this. [6]

The problem is that it is only possible to configure a single 40 MHz channel when using 2.4GHz band.

If we use a 40 MHz bandwidth for one channel, the channel map would result as Fig.7.

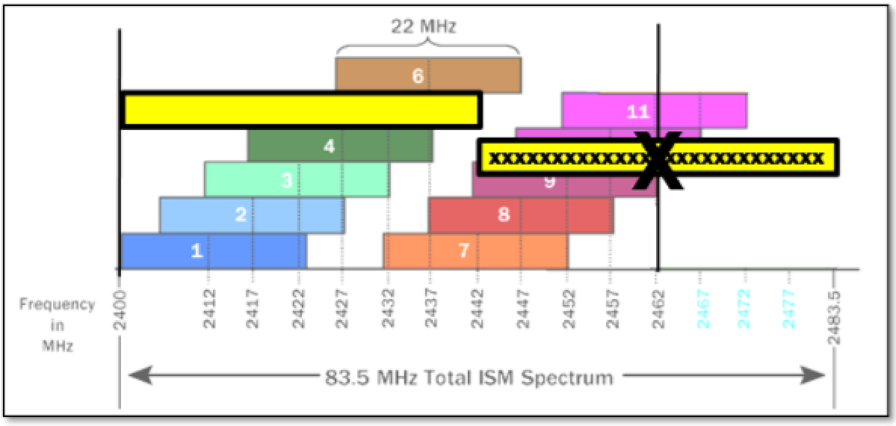


Fig.7. Using 40MHz bandwidth in 2.4GHz band [6]

Showing that the only option where 40 MHz bandwidth channels can be used in 2.4 GHz band would be as Fig.7 illustrates, due to the reason that two 40 MHz channels cannot co-exist in another way due to overlapping.

That is not a reasonable or useable option for most commercial wireless LAN implementations.

That is the reason that only 5 GHz band has enough channels to make 40 MHz commercial implementation feasible.

5.3.2 5 GHz BAND

5 GHz band apart from its function of making 2.4 GHz band less congested due to the massive growth of devices connected at this frequency, it has the property to allow 40 MHz bandwidth channels which means higher data rates through the physical layer, in other words, twice the throughput capacity of 20MHz channel.

The 5 GHz band has relatively reduced interference and there are a greater number of non-overlapping channels available (25 non-overlapping channels in US) compared to the 2.4 GHz band (3 non-overlapping channels in the US).

The channel allocation for 5GHz band is illustrated in Fig.8 and Fig.9 where it shows the clear difference of the number of non-overlapping 40 MHz channel respect using 2.4GHz band where it would only have 1 possibility of non-overlapping. [8]

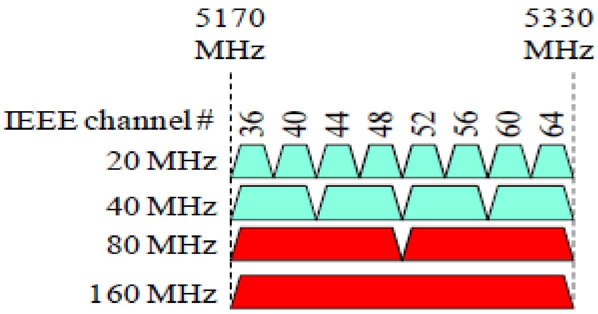


Fig.8 US 5GHz Channel allocation [8]

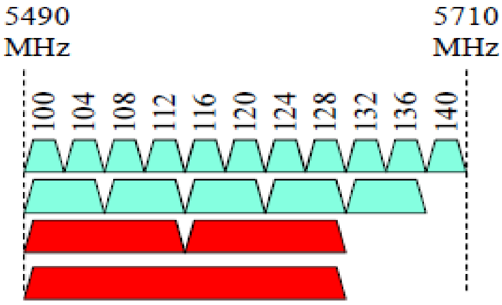


Fig.9 Europe, Japan and Global Operation Class 5GHz Channel Allocation [8]

5.4 OFDM

Once explained how the radio frequency spectrum is divided in channels in order to send the data, we focus in OFDM.

OFDM (Orthogonal Frequency Division Multiplexing) is a form of signal modulation that divides a high data rate modulating stream placing them onto many slowly modulated narrowband close-spaced subcarriers and in this way is less sensitive to frequency selective fading.

Frequency selective fading as we explained in previously sections is a radio propagation anomaly caused by partial cancellation of a radio signal due to the signal arrives at the receiver by two different paths, and at least one of the paths is changing (lengthening or shortening).[9]

5.4.1 WHY OFDM

Modulation methods become problematic at high data rates.
As the required data increases, the symbol duration becomes very small and the system bandwidth becomes very large.

If the symbol duration becomes very small, then, the impulse response of the equalizer becomes very large in terms of symbol duration, which means a high computational effort for the equalizer and the probability of instability increases.

A great feature in OFDM is that it increases the symbol duration on each of its carriers making narrow bandwidth subcarriers, thus a simple equalizer can be used for each subcarrier.

5.4.2 PRINCIPLE OF ORTHOGONAL

We previously commented why the sub-carriers are orthogonal to each other avoiding selective fading we previously named.
The term "orthogonal” is actually an adjective describing two things acting independently or in an uncorrelated manner; in this case, any two signals of an OFDM based product operating without dependence on, or interference with, one another.

OFDM splits a high-rate data stream into N parallel streams. Therefore, symbol duration of each subcarrier becomes larger by a factor of N.

By having a large carrier spacing between the carriers, receivers can achieve the demodulation of the transmission without troubles as fig.10 illustrates.[4]

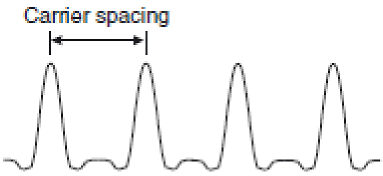


Fig.10. Carrier Spacing using large frequency spacing [1]

However, applying carrier spacing as Fig.10, high amount of spectrum would be wasted and that is the reason where in OFDM signals carried by different subcarriers have to be orthogonal.

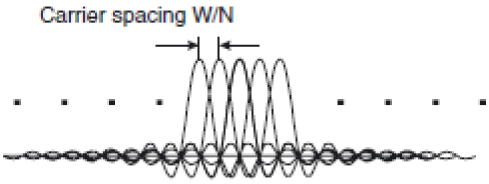


Fig.11. Concept of Orthogonal (Carrier Spacing) [1]

Fig.11 illustrates the concept of orthogonal where due to the rectangular shape of pulses in the time domain, the spectrum of each modulated carrier has a sin(x)/x shape.

The spectra of different carriers overlap, but each carrier is in the spectral nulls of other carriers. Therefore, data streams of any two subcarriers will not interfere.

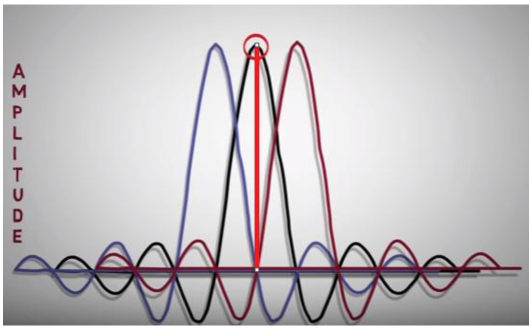


Fig.12. Concept of Orthogonal (No interference) [10]

As Fig.12 shows, the maximum amplitude peak of the carrier coincides with the spectral nulls of the other carriers, that is how “no interference” between carriers is achieved.

5.4.3 SUBCARRIERS

OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel.

Each subcarrier is modulated with a not complex digital modulation scheme such as QPSK or 16QAM at a low symbol rate.

The combination of these carriers enables data rates similar to single carrier modulation schemes with equivalent bandwidths.

In the case of 802.11n, it allows for 56 subcarriers of which 52 are usable for data with a 20MHz wide channel and 144 subcarriers of which 108 are usable for data with a 40MHz wide channel.[6]

5.4.4 MULTIPLEXING

Finally, OFDM is based on FDM (Frequency Division Multiplexing), technique where the frequency band is split into small frequency channels in order to send information through these channels. Each FDM channel is separated from the others by a frequency guard band to reduce interference between adjacent channels.

However, OFDM scheme differs from FDM in:

- Multiple carriers (called subcarriers) carry the information stream in the frequency given.
- The subcarriers are orthogonal to each other.
- A guard interval is added to each symbol to minimize the channel delay spread and Intersymbol interference.

Although the sidebands from each carrier overlap, they can still be received without the interference that might be expected because they are orthogonal to each another. This is achieved by having the carrier spacing equal to the reciprocal of the symbol period.

5.5 MIMO ANTENNA

MIMO (Multiple-input multiple-output) is a radio communication technology or RF technology based on space diversity that make use of reflected signals to provide gains in channel robustness and throughput.

Currently, in order to transmit signals efficiently, parameters as time, frequency and space can be modified.

As an example, time diversity is used in transmissions where same message is transmitted at different time slots or frequency diversity is used in transmissions where the same message is transmitted at different frequencies.

What is characteristic of MIMO technology is the use of space diversity, based in the use of separate antennas which are located in different positions to take advantage of the different paths that exist in a typical terrestrial environment.

5.5.1 SPATIAL DIVERSITY OR SPATIAL MULTIPLEXING

Existence of multiple antennas in a system means existence of different propagation paths.

In order to improve the reliability of the system, we may choose to send same data across the different propagation paths. There are two methods we can apply:

On the one hand, spatial diversity sends the same information across independently fading channels to combat fading.

When multiple copies of the same data are sent across different propagating fading channels, the amount of fade suffered by each copy will be different. This guarantees that at least one of the copies will suffer less fading than the others, thus more probabilities of receiving the information without errors.

On the other hand if we use spatial multiplexing method, each antenna/channel carries independent information, thus, increasing the data rate of the system. This can be compared to OFDM technique where different frequency sub channels carry different parts of the modulated data.

Spatial multiplexing is frequently used when the scattering by the environment is rich. In other words, there are no scatter elements to interfere the signal. Therefore, if the situation is as explained before, several independent sub channels are created in the same allocated channel.[11]

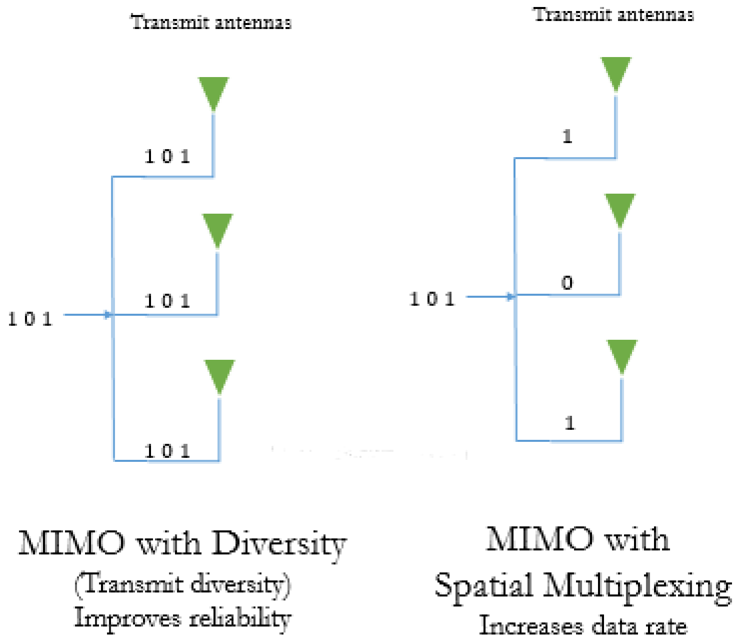


Fig.13 MIMO transmissions using Spatial Diversity and Spatial Multiplexing [11]

5.5.2CONFIGURATIONS

Several MIMO configurations or formats are used.

SISO, SIMO, MISO and MIMO require different numbers of antennas as well as having different levels of complexity. [7]

- SISO - Single Input Single Output
- SIMO - Single Input Multiple output
- MISO - Multiple Input Single Output
- MIMO - Multiple Input multiple Output

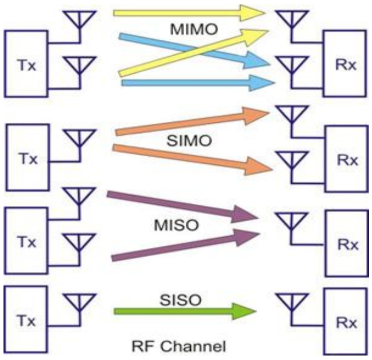


Fig.14 Comparison MIMO technologies [7]

Diversity path is the number of paths available from the transmitter to the receiver. Fig.14 shows the different paths when using different configurations.

Diversity path increases when increasing the number of antennas.

As an example, for MIMO (2X2) (2 antennas for the transmitter and 2 antennas for the receiver) we obtain a diversity path of 2 x 2 = 4 different paths.

It means, that there will be 4 different paths affected by different levels of fading, thus depend on the situation, more chances and possibilities to receive the information with the less interference possible.

MIMO embraces (2x2), (2x4) , (4x2) and (4x4) number of antennas.

Finally, by increasing the number of antennas taking part in the transmission, the receiver will require additional signal processing techniques in order to restructure the received signals by different paths.

6. INDOOR CHANNEL MODEL

The indoor channel corresponds to the small coverage areas inside the building such as offices, flats or establishments.

Since these environments are enclosed by a wall , the power spectrum tends to be uniform due to scattered components from reflected signals will be received from all directions with the same power.

Furthermore, the mobility of the terminals inside the building have low mobility, thus the channel tends to be also static.

However, the channel condition may vary with time and location which still requires a profile to represent the channel delays and their average power.

For the design, simulation and planning of wireless systems in indoor environments, we need models for the propagation channels.

In this chapter we discuss in a more concrete way how to parameterize these models.

In order to create an accurate channel model in the specific environment, we must have full knowledge on the characteristics of reflectors and the power of the reflected signal at a given time.

Since such characterization is not possible in reality, we resort to the specific channel which can represent a typical or average channel condition in the given environment.

Through this section, we first introduce the two most popular indoor channel models:

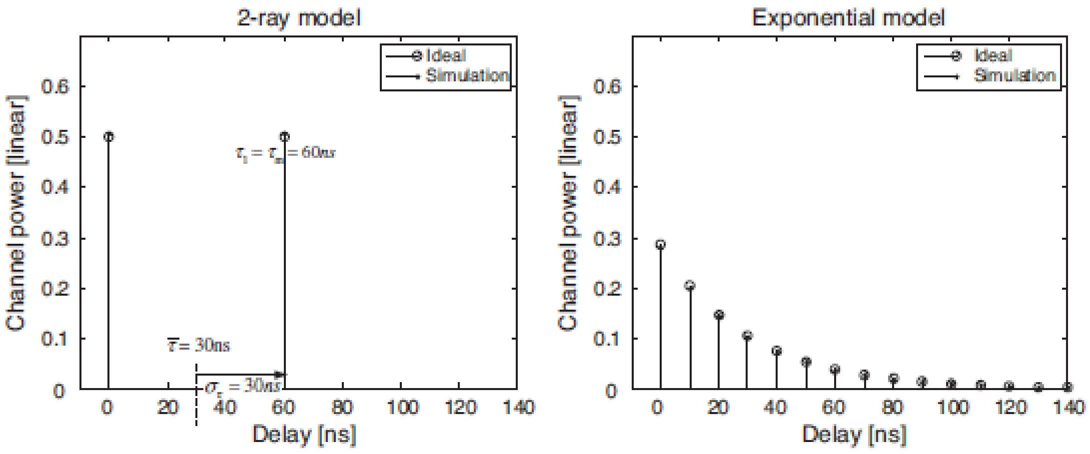
6.1Two-ray model

First of all, 2-ray model is an interesting and useful channel model due to all the scenarios consider one direct path and one reflected path.

In the two-ray model, there are two rays, one for a direct path with zero delay and the other for a path which is a reflection with delay t1>0, each with the same power.

In other words, the delay of the second path is the only parameter that determines the characteristics of this model.

However, it is not accurate because in practice, the magnitude of the second path is usually much less than that of the first path. Therefore, this model is useful and effective in those scenarios where there is a significant loss in the first path. [12]



(a) 2-ray model (b) Exponential model

Fig.15. ray-model vs exponential model [1]

Fig.15 (a) illustrates in discrete domain “2-ray” channel model and “exponential” model we will see in the next section.

6.2Exponential model

As Fig.14 (b) shows, in the exponential model, the average channel power decreases exponentially with the channel delay as follows:

$$\mathrm{P}\ (\tau) = \frac{1}{\tau d} e^{-\frac{\tau}{\tau d}} \qquad (1)$$

Where τd (mean excess delay) is the only parameter that determines the power delay profile we see in Fig.14 (b).

This model is also appropriate for an indoor channel environment. [1]

6.3 802.11 model

An evolution of the two models presented before is 802.11 model.

As an example IEEE 802.11b has adopted the exponential model previously explained to represent a 2.4 GHz indoor channel.

A channel impulse can be represented by the output finite impulse response (FIR) filter and each channel tap is modeled by an independent complex Gaussian random variable with its average power that follows the exponential model. [1].

6.4Salah Valenzuela model

Finally, one of the most popular channel model for indoor multipath propagation was proposed by Adel A. M. Saleh and Reinaldo A. Valenzuela.

Their work consisted of collecting temporal data on indoor propagation, from which they proposed a time domain model. Their model is based in a clustering phenomenon where the arrivals come in groups/clusters.

In other words, it states that rays arrive to receiver in clusters which is the consequence of reflections from large scatterers present inside the environment.[14]

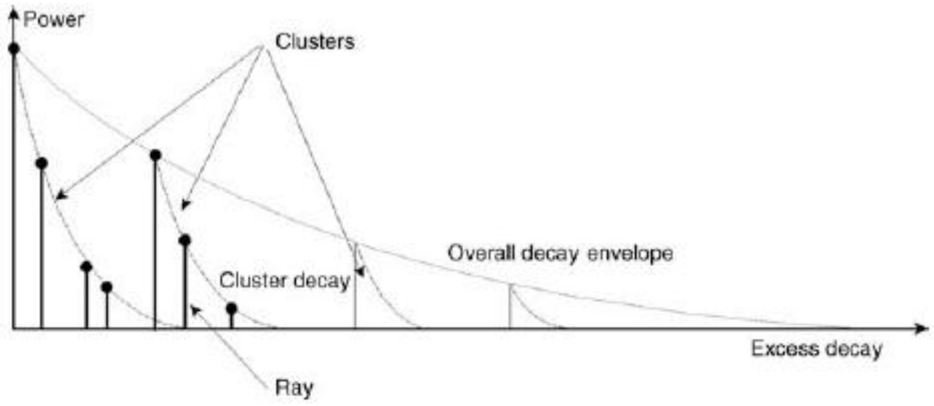


Fig.16. Cluster structure in Saleh- Valenzuela model [12]

As Fig.16 illustrates, the time of arrival is described by two Poisson processes which model the arrival times of clusters and the arrival times of rays within clusters. The time of arrival of each cluster is an exponentially distributed random variable conditioned on the time of arrival of the previous cluster. The case is the same for each ray, or arrival within the cluster. [13]

Some considerations in the model are:

On the one hand, the first arriving cluster of rays is formed basically by “direct” path rays to the receiver which is not usually a straight line and comprises mostly open spaces and goes through a few but not too many walls.

On the other hand, second cluster is not always present for every situation and depending on the line of sight from the transmitter to the receiver it will appear attenuated in amplitude respect the previous cluster. Fig.16 illustrates this phenomenon where clusters, and rays within clusters are attenuated with delay time.

Fig.17 could be a more technical representation about how the signal arrives in clusters.

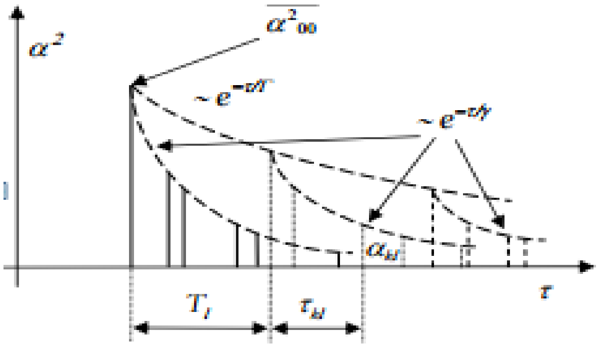


Fig.17. Cluster structure in Saleh- Valenzuela model with parameters [15]

In this case, Fig.17 will help to understand the parameters that take part into S-V channel model.

First of all, the channel impulse (1) response may be written as:

$$h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} \exp\,(j\phi_{kl})\delta(t - T_l - \tau_{kl}) \qquad (1)$$

Where:

Index "l" indicates the cluster number and index "k" indicates the echo ray number within a cluster.

- β_{kl} is the mean amplitude of the k-th ray inside l-th cluster
- ϕ_{kl} is the phase of the ray
- δ is Dirac delta function
- T_l is the relative delay of the l-th cluster
- τ_{kl} is the relative delay of the k-th ray

As we previously said, and as Fig.17 shows, T_l and τ_{kl} are described by independent inter-arrival exponential density functions, thus, the envelopes will take different curve exponential shapes in each case [15].

In other words, the number of arrivals and times of arrival for both clusters and rays are characterized by means of Poisson and exponential distributions,,,,, (2),(3). Distributions of these arrival times are as follows:

$$\rho\ (\text{-}T_l/T_{l-1}) = \Lambda\exp[\text{-}\Lambda\ (-T_l/T_{l-1})] \quad T_{l-1} < \ T_l \ < \ \infty \qquad (2)$$

$$\rho(\tau_{kl}|\tau_{(k-1)l}) = \lambda\ \exp[\text{-}\lambda\ (\tau_{kl} - \tau_{(k-1)l})] \quad \tau_{(k-1)l}\ < \ \tau_{kl}\ < \ \infty \qquad (3)$$

λ is the ray arrival rate and Λ is the cluster arrival rate .Ray arrivals within the clusters are realized by the second Poisson process with rate λ >>Λ. Besides of arrival times, the received rays structure presents a decay rate defined by β_{kl}^2 where:

$$\beta_{kl}^2 = \beta^2(0{,}0)\exp(\text{-}T_l/T)\exp\ (\tau_{kl}/\gamma) \qquad (4)$$

- β^2(0,0) is the average power of the first arrival in the first cluster
- γ is the decay rate within each cluster
- T is the cluster decay rate

With all these parameters explained and having knowledge of the theory, we are prepared to elaborate the code in Matlab that will show statistical parameters of this model.

6.4.1 MATLAB

The aim of this section is to elaborate a S-V channel model and try to analyze the results when using frequencies at 2.4 GHz in different types of environments .

In order to generate a S-V channel model, we first need some useful parameters to model it.

One consideration we have to take into account before starting to create the model is that distances between transmitter and receiver are much smaller for indoor areas due to the high attenuations introduced by walls, floors, roofs and furniture.

For this reason, when using the formula to calculate the free space loss for indoor areas where coefficient “n” takes part in, we have to consider different possible values for “n” depend on the line of sight between the transmitter and receiver.

Typical values of “n” are about 3 for LOS paths (in open spaces), 4 for OLOS paths (where thin walls or objects block the direct signal) and 6 for NLOS paths (where thick walls block the direct signal).

Once this clear, we can apply (5) for the power received with free space loss where “n” plays a role.

$$\mathrm{P_r(d) = EIRP - \ L_{fs}(1m) - \ 10nlog(d)dBm} \qquad (5)$$

The code to generate the channel model is shown and explained as follows:

```
%ENVIRONMENT PARAMETERS

freq=2400;   % frequency in MHz
dist=30;      % distance in m between transmitter and receiver
n=4;        % propagagation exponent depend on the line of sight between transmitter and receiver
EIRP=1;      % EIRP in dBW

% S&V MODEL PARAMETERS

raylambda=5;       %  ray arrival rate in ns^-1
clustlambda=25;   % cluster arrival rate in ns^-1
raygamma=30;      %  ray decay factor in ns
clustgamma=50;   % cluster decay factor in ns


% BUTTERWORTH FILTER PARAMETERS [12]

fs=20;        % Sampling frequency in Hz
Wp=0.01;    % Normalized frequency wrt fs/2. Passband
Ws=0.2;      % Normalized frequency wrt fs/2. Stopband
Rp=3;         % Passband spec in dB
Rs=40;       % Stopband spec in dB
leng=500;    % Simulated series length

lambdac=300/freq;

% FREE SPACE LOSS AND RECEIVED POWER AT 1m FROM TRANSMITTER

Lfs1m=32.4+20*log10(1/1000)+20*log10(freq);  % Free space loss at 1 m distance

Pr1m=EIRP-Lfs1m;           % Received power at 1 m assuming Gr=0 dBi;

Pr=Pr1m-10*n*log10(dist)   % Received power under an “n” propoagation law

Lfsdm=32.4+20*log10(dist/1000)+20*log10(freq); % Free space loss at dist m

Prfs=EIRP-Lfsdm           % Received power under fs conditions (dBW)
```

```
prRelativedB=Pr-Prfs      %Received power relative to free space. We will use this value to generate the powers of clusters and rays later.(dB)

%GENERATE CLUSTER ARRIVALS

NClusters=100;   % These arrivals are not used all in the end

% Generate exponential inter-arrivals with cluster arrival rate parameter and the number of clusters

Texp=genExponential(clustlambda,NClusters);

Texp=[0;Texp];                          % First arrival is at 0 ns
TClusters=cumsum(Texp);           % We have all the clusters in time
prClusters=ones(length(Texp),1);  % We start with all cluster powers at same value “1”


figure,stem(TClusters,prClusters)
xlabel('Times of arrival of clusters (ns)')
ylabel('Uniform cluster powers')



% CLUSTER POWER DECAY DEPEND ON GAMMA

% Apply power decay rate by multiplying the clusters we have at the same level “1” to the exponential power decay rate depend on gamma value

prClusters=prClusters.*exp(-TClusters/clustgamma);

Delta=prRelativedB-10*log10(sum(prClusters))  % Compute difference with objective
prClusters=prClusters*10.^(Delta/10);             % Correct powers to fit objective


figure,stem2D(TClusters,10*log10(prClusters),-80)
xlabel('Times of arrival of clusters (ns)')
ylabel('Cluster powers (dB)')
grid
```

```
% SELECT SIGNIFICANT CLUSTERS

stopT=find(10*log10(cumsum(prClusters))>prRelativedB-0.5);  % Within 0.5 dB
stopT=min(stopT)         % Select first

TClusters=TClusters(1:stopT);
prClusters=prClusters(1:stopT);

% Now we have all the clusters in time with the real power given by the EIRP, path loss and the
exponential function depend of S-V parameters

figure,stem2D(TClusters,10*log10(prClusters),-80) % Expressed in dB
xlabel('Times of arrival of clusters (ns)')
ylabel('Cluster powers (dB)')
grid

figure,stem(TClusters,prClusters)
xlabel('Times of arrival of clusters (ns)')
ylabel('Cluster powers')
grid


% WITHIN EACH CLUSTER, RAY DELAYS AND AVERAGE POWERS

NClusters=length(TClusters)

prClustersdB=10*log10(prClusters);
NRayArrivals=100;

TimeTotalRays=[];
PowerTotalRays=[];

for ii=1: NClusters

%GENERATE RAY ARRIVALS FOR CLUSTER ii

Texp=genExponential(raylambda,NRayArrivals);
Texp=[0;Texp];         % First arrival is at 0 ns
TRays=cumsum(Texp);
prRays=ones(length(Texp),1);
```

```
% RAY POWER DECAY DEPEND ON gamma

prRays=prRays.*exp(-TRays/raygamma);
DeltaPower=prClustersdB(ii)-10*log10(sum(prRays));
prRays=prRays*10.^(DeltaPower/10);


% SELECT SIGNIFICANT RAYS

stopT=find(10*log10(cumsum(prRays))>prClustersdB(ii)-0.5);  % Within 0.5 dB
stopT=min(stopT);         % Select first

TRays=TRays(1:stopT);
prRays=prRays(1:stopT);


TimeTotalRays=[TimeTotalRays; TRays+TClusters(ii)];
   PowerTotalRays=[PowerTotalRays; prRays];

end

figure,stem2D(TimeTotalRays,10*log10(PowerTotalRays),-80) % Expressed in dB
xlabel('Times of arrival of rays (ns)')
ylabel('Ray power (dB)')
grid

figure,stem(TimeTotalRays,PowerTotalRays)
xlabel('Times of arrival of rays (ns)')
ylabel('Ray power')
grid
```

6.4.2STATISTICAL DISTRIBUTIONS

We start showing the main statistical results for a frequency of **freq**=2.4GHz, distance between the transmitter and receiver **dist** =30 m, a propagation exponent **n**=3 (LOS path) and an **EIRP** of 1dBW. Furthermore, S-V parameters 1**/Λ**=30ns **1/λ**=5ns ***γ***=30ns and **T**=60ns.

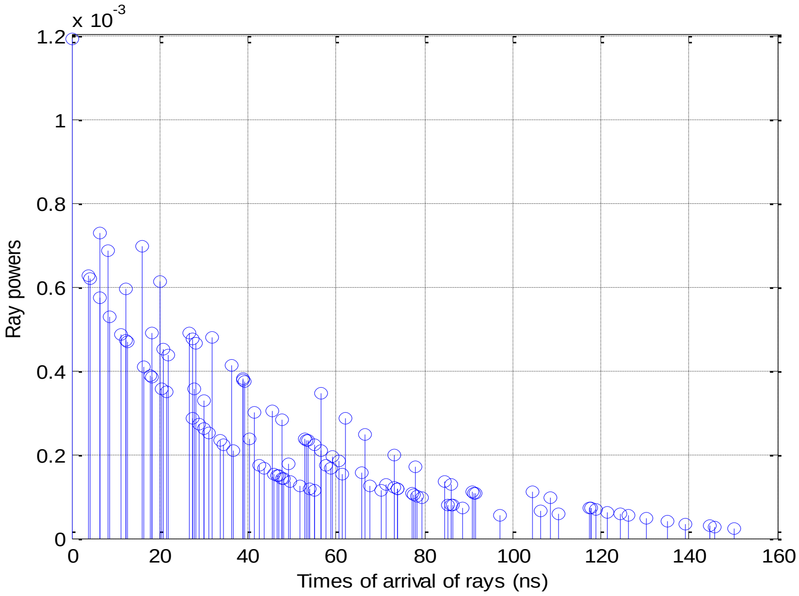


Fig.18. Ray powers for n=3

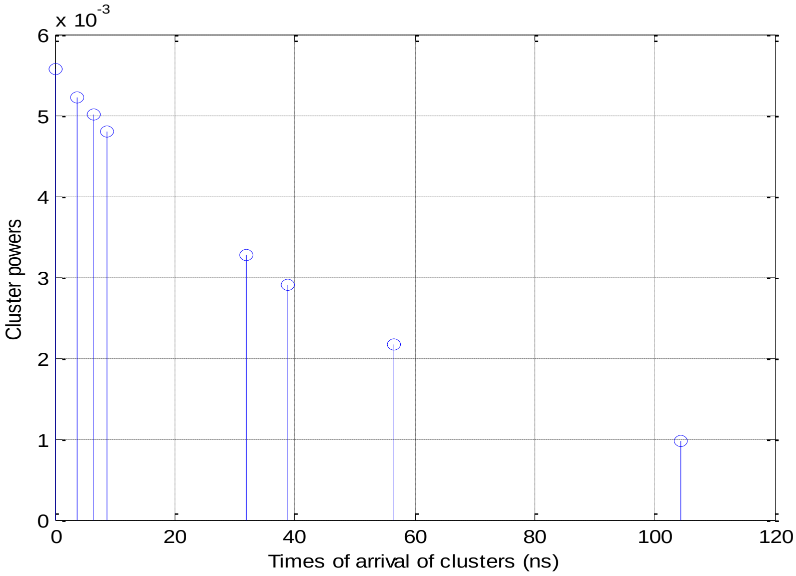


Fig.19.Cluster powers for n=3

Now, we show the statistical results for a frequency of 2,4GHz , distance between the transmitter and receiver 30 m , a propagation exponent n=6 (LOS path) and an EIRP of 1dBW with the same S-V parameters. What we did here, is only to change the coefficient “n” from 3(LOS) to 6(NLOS).

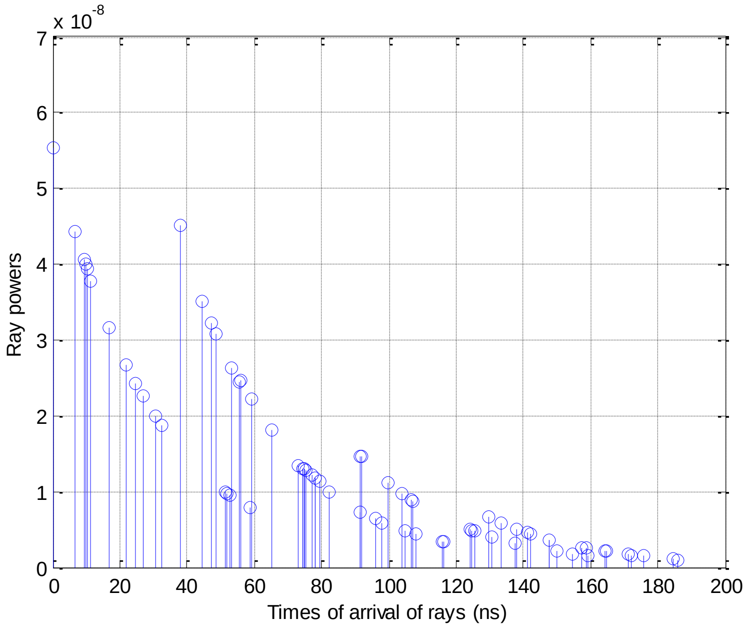


Fig.20.Ray powers for n=6

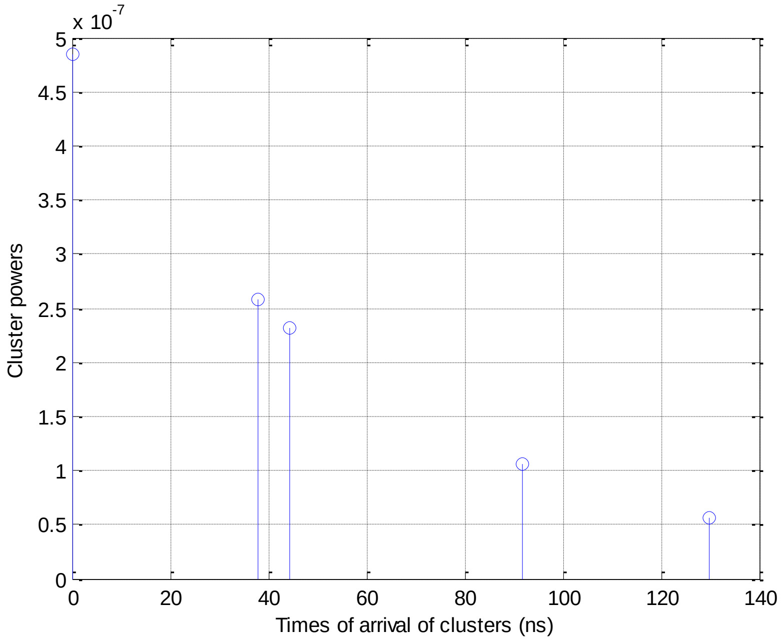


Fig.21.Cluster powers for n=6

Some conclusions we can take with these results, is that, by modifying parameter “n” from n=3(LOS path) to n=6(NLOS path), we observe an important reduction of the ray and cluster powers for NLOS path which is coherent with the theory.

On the other side we modify now S-V parameters.

With same environment parameters as before and with the S-V parameters **1/Λ**=30ns **1/λ**=5ns γ=30ns and **T**=60ns. If we modify the cluster decay factor to **T** =300 ns instead of **T** =60ns.

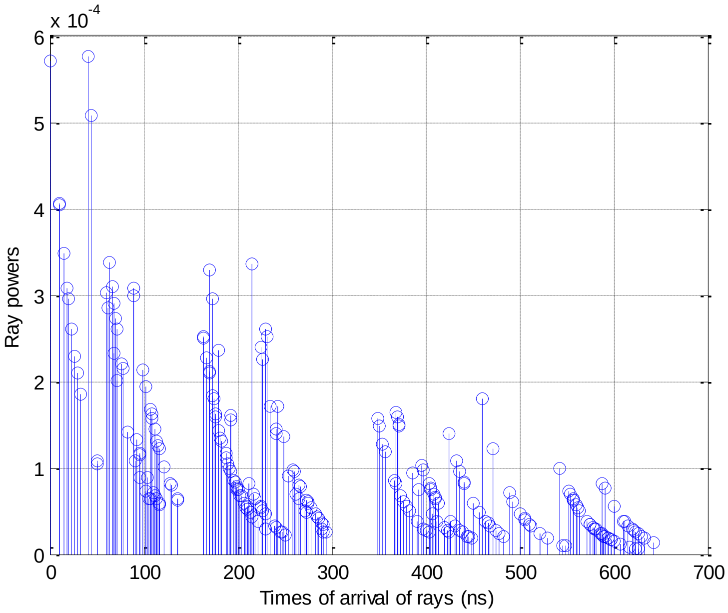


Fig.22. Ray powers with **T** =300 ns

We observe in Fig.22 a more steep exponential envelope between every cluster.

On the other hand, if we keep the cluster decay factor $\mathbf{T}$ =60 and now we increment the ray decay factor to $\boldsymbol{\gamma}$ = 300 instead of $\boldsymbol{\gamma}$ = 30,

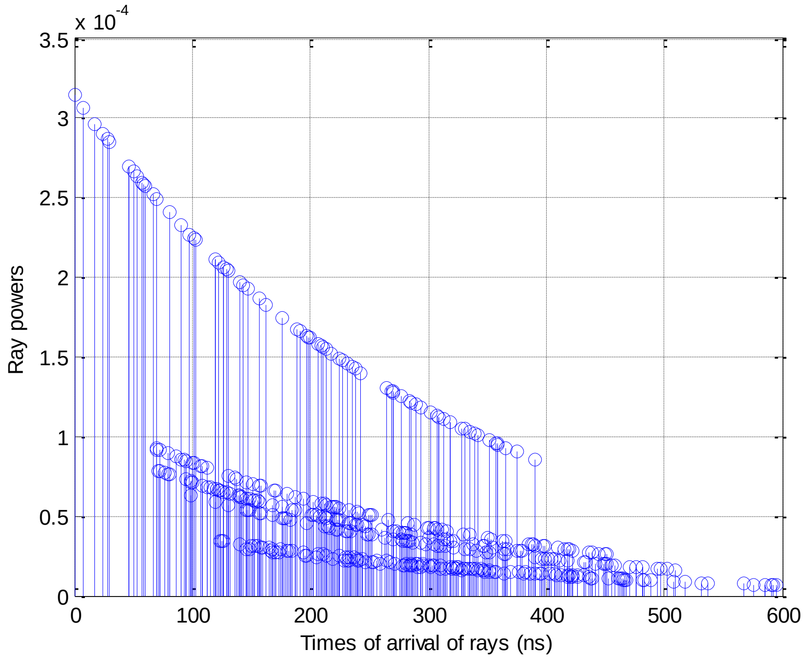


Fig.23. Ray powers with $\boldsymbol{\gamma}$ = 300

We observe that ray decay rate is given with less frequency (more “ns” has to pass), thus, an envelope less steep between each ray.

To sum up, by modifying any parameter , what we observe it is given in all cases is that rays arrive in clusters with more or less power, but in clusters.

7. APPROPIATE CHANNEL MODEL FOR OFDM SYSTEMS

Channel models are the foundation on which mobile communications systems are built.

One of the topics in this thesis was the design of OFDM interfaces. For that, once explained the different channel models, in this chapter we will discuss an appropriate channel model for such systems.

As the systems have evolved, demand for higher transmission rates has been increasing making the channel’s time dispersion (which is equivalent to its frequency selectivity) a major issue.

According to the specifications, the channel should fit into physical radio channels in the millimeter-wave frequency band for indoor areas. A brief review of the model Saleh-Valenzuela model is given in this chapter, discussing a number of modifications for its application to millimeter-wave channels. [17]

7.1 Modifications to the model

Several authors have applied a number of modifications to the Saleh-Valenzuela model described in section 6.4 that consists in reducing the number of clusters that arrive to the receiver to one.

This simplification is made because in a typical indoor millimeter-wave channel, the reflections came mainly from one dense cluster of ray arrivals as frequencies hardly penetrate through building material.

Therefore, a single cluster of rays is an appropriate description of millimeter-wave indoor channels, where the transmitter and receiver are typically located within the same room.

8. CONCLUSION

Through this thesis we understood the principal types of fading that affect our wireless transmissions in indoor areas.

We also explained the physical layer of IEEE 802.11n remarking the use of OFDM to prevent multipath fading and the use of MIMO to generate several paths in order to improve the signal and contributing to a better reception signal quality.

A brief description of different channel models has been given, emphasizing Saleh-Valenzuela model where we observed that rays generally arrive in clusters where amplitude of both clusters and rays decay exponentially with delay time.

Finally we found an appropriate channel model for OFDM systems adapting Saleh-Valenzuela channel model by reducing the number of clusters received to one only cluster.

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Title: Typical indoor cannel models and their influence on OFDM signal

Summary: After the description of the phenomenon of fading in indoor channel and the physical layer of IEEE 802.11n with a focus in OFDM, a program in Matlab is generated to show the statistical distributions of main parameters of such generated channels.

Especially the thesis goes deep into Saleh-Valenzuela channel model.

Keywords: Fading, multipath, propagation, OFDM, rays, cluster, Saleh-Valenzuela, channel, model, delay, WLAN, indoor, variation.