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Narrowband 5 GHz Mobile Channel Characterization

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NARROWBAND 5 GHz MOBILE CHANNEL
CHARACTERIZATION

by

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B.A., Pontificia Universidad Catolica del Peru, 2007

A thesis submitted to the
Faculty of the Graduate School of the
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of the requirement for the degree of
Master of Science
Interdisciplinary Telecommunications Program
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This thesis entitled:
Narrowband 5 GHz mobile channel characterization
written by Nadia P. Yoza Mitsuishi
has been approved for the Interdisciplinary Telecommunications Program

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Dr. Jim Lansford

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Dr. Robert Johnk

Date

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.
Yoza Mitsuishi, Nadia Patricia (M.S., Interdisciplinary Telecommunications Program)

Narrowband 5 GHz mobile channel characterization

Thesis directed by Professor Ken Baker

This work contains measurements and characterization of 5 GHz mobile radio channel along indoor and indoor to outdoor paths using a novel narrowband propagation measurement system. This system consists of a vector signal analyzer and highly stable oscillators. The stability and precision of the system permit post-processing the baseband complex received signals in order to analyze the channel characteristics. We have performed narrowband measurements on the 5.41 GHz mobile radio channel in four different scenarios: indoor with line of sight, indoor through walls, indoor through different floors and indoor to outdoor considering in-building penetration. The data collected has been processed for estimating the path loss, fading statistics and Doppler power spectrum for each scenario. We show that the processing permits the extraction of information about the scattering environment. The results permit characterizing the 5 GHz mobile radio channel for future spectrum sharing designs, as well as for network planning and capacity planning for WiFi and cellular applications in this band.
To my parents:

Teodoro and Elena
Acknowledgements

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CHAPTER 1

1 INTRODUCTION

Recently, the 5 GHz bands have become increasingly attractive for the wireless industry due to the large amount of unlicensed spectrum available and less congested than the 2.4 GHz band. This is the reason why three WiFi standards operate in the 5 GHz band and its use is also being proposed for LTE-U (LTE-Unlicensed), which will use the unlicensed spectrum in this band for increasing the capacity of LTE (Long-Term Evolution) networks. However, meteorological and military radars also operate in this band. In this context, it is necessary to perform additional propagation and interference studies in order to characterize the 5 GHz mobile radio channel considering its current uses and future applications.

1.1 Objective and motivation

The objective of this research is to characterize the 5 GHz mobile radio channel in indoor and indoor to outdoor environments using a novel mobile narrowband propagation measurement system. This system, developed at the Institute for Telecommunications Sciences (NTIA/ITS), will permit us to characterize the path loss, the fading statistics for line-of-sight (LOS) and non-line-of-sight (NLOS) conditions and the scattering environment, based on Doppler effects.

The ultimate purpose of this study is to understand the mobile radio channel at 5 GHz, including the scattering environment, to enable new uses of this band. Possible future uses include spectrum sharing techniques between different technologies in this band, such as WiFi and the proposed LTE-U. Therefore, considering the potential of the 5 GHz band in new wireless deployments, the results of this research will constitute a powerful reference for the analysis of
spectrum sharing capabilities, between indoor users as well as indoor and outdoor sharing. Additionally, it will provide useful information for network and capacity planning for the design of WiFi and LTE-U networks in this band.

1.2 Thesis statement

This work will focus on two main aspects. First, we will prove that the novel measurement system used is highly precise, flexible and stable and permits many data post-processing options in a simple and accurate way. Additionally, the measurements obtained will permit to characterize the 5 GHz mobile radio channel by estimating the path loss, Doppler power spectrum and fading statistics for indoor and indoor to outdoor paths in an office building environment.

1.3 Research question and sub-problems

In this context and considering the parameters that will be measured using the system, the research question is the following:

What are the path loss, Doppler power spectrum and fading statistics of the 5 GHz mobile radio channel in indoor and indoor to outdoor environments that can be estimated using this novel narrowband mobile propagation measurement system?

In order to address this question, the research will be divided into four sub-problems and each of them will represent a set of scenarios of study in order to characterize the indoor and indoor to outdoor propagation for different factors. For each of these scenarios, we will measure the received baseband complex I-Q signal using a static transmitter and a mobile receiver, both
set at an operating frequency of 5.41 GHz. The collected I and Q data will be processed and analyzed in order to estimate the path loss, Doppler power spectrum and fading statistics for each scenario. These parameters will permit the modeling of the mobile radio channel for the propagation conditions studied in this band.

The propagation characteristics will be different for each scenario and they will depend on the structure and layout of the building that will be measured. Therefore, in order to characterize indoor and indoor to outdoor mobile propagation as accurately as possible, we will choose a representative office building of modern construction where it will be possible to identify the four sets of scenarios that will be analyzed in this research. These scenarios are indicated below:

a) Indoor line of sight: It will require that the transmitter and the receiver are located in the same corridor. Since there will be line of sight between both of them, we expect the fading to have a Rician distribution [1][2][3].

b) Indoor through walls: The receiver will be located in another room on the same floor in order to study the propagation through walls. A line of sight condition is not expected and the fading will follow a Rayleigh distribution [1][2][3].

c) Indoor through different floors: In this case, the receiver will be located on another floor and, because of the structure of the building, the attenuation is expected to be significantly higher than in the case of propagation through walls on the same floor.

d) Indoor to outdoor: The transmitter is fixed and located inside the building, while the receiver is moved outside the building. This will permit the study of building penetration and other characteristics of this indoor to outdoor mobile propagation.
The measurements of the received signals and the analysis of the propagation characteristics will enable us to address the research question and, therefore, characterize indoor and indoor to outdoor propagation for 5 GHz mobile radio channels.

1.4 Organization

The thesis is organized in five chapters. The remainder of this work presents the following structure:

- Chapter 2 presents the literature review on radio propagation and theoretical background about the 5 GHz mobile radio channels and previous studies performed in this band.
- Chapter 3 describes the measurement system, the procedure used for performing the measurements and the data processing implemented for calculating the radio channel parameters.
- Chapter 4 describes each measurement scenario and presents plots that show the path loss, Doppler power spectrum and fading characteristics for each of them. The results are analyzed, compared for the different propagation conditions studied and contrasted with previous measurements performed.
- Chapter 5 provides the conclusions and proposes future directions for this work.
CHAPTER 2

2 LITERATURE REVIEW

This chapter presents a review of the theoretical concepts used in this work. It provides a background on the structure and applications on the 5 GHz band, concepts on radio propagation and path loss models for indoor environments, data processing techniques for channel parameters estimation and information about previous measurements on this band.

2.1 Background on 5 GHz band

The 5 GHz U-NII (Unlicensed National Information Infrastructure) band comprises three frequency bands that use four frequency ranges:

- U-NII-1: 5.15-5.25 GHz
- U-NII-2a (middle): 5.25-5.35 GHz
- U-NII-2c: 5.47-5.725 GHz
- U-NII-3: 5.725-5.825 GHz, which overlaps with the ISM band.

The channel planning and the operation in each of them are described in Figure 2.1. In order to encourage new and further technologies and, at the same time, protect the existing services from harmful interference, the FCC has recently made some regulatory modifications, which will permit more flexibility and a higher utilization of this 5 GHz band for commercial uses. In March 2014, the FCC announced some changes in the use of the U-NII bands [4][5]. They are described in the next paragraphs.

First, the U-NII-1 band, originally limited to indoor use only, can now be used outdoors. Also, the FCC increased the permitted power, with the aim of increasing the utility and
availability of the spectrum needed for the next generation of Wi-Fi technology. Past regulations allowed only a maximum transmission power of 50 mW using an integrated antenna. With the new regulation, the maximum conducted output power is 1 watt. The maximum EIRP is 4 watts (+36 dBm) for point-to-multipoint configurations and 200 watts (+53 dBm) for point-to-point. Additionally, the assumed antenna gain is 6 dBi, with a 1 dB decrement in the output power for every dB that the antenna gain exceeds 6 dBi.

Additionally, U-NII-3 band is now extended. The upper edge will be 5.85 GHz and, thus, this band will cover 5.725-5.85 GHz, adding 25 MHz of bandwidth. Furthermore, U-NII-3 band will be removed from part 15.247 rules, applied to devices operating under the ISM bands, except for frequency hopping systems. This modification will allow better support and additional spectrum available for wideband digital modulation techniques which will allow higher data rates that can be achievable with 802.11ac. The maximum conducted output power remains at 1 watt.

Another policy states that all U-NII device software should now be secured to prevent its modification. This will ensure that the devices will operate as authorized by the FCC, reducing the risk of harmful interference to authorized users.

Finally, technical rules and compliance measurement procedures have been modified for devices operating in the U-NII-2 band in order to protect Terminal Doppler Weather Radar (TDWR) systems and other radar systems operating in this band from harmful interference.
## Operation in U-NII Bands – 802.11 Channel Plan

**§15.407 (Part 15E), 1st R&O (FCC 06-96), effective 6/2/2014**

### Frequency Range (MHz)
- 5150-5350
- 5250-5350
- 5470-5725
- 5725-5850

<table>
<thead>
<tr>
<th>Condition of Operation</th>
<th>5150-5350</th>
<th>5250-5350</th>
<th>5470-5725</th>
<th>5725-5850</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Conducted TX Power</td>
<td>30 dBm (1 W) for mobile/portable devices</td>
<td>24 dBm (250 mW) for mobile/portable devices</td>
<td>24 dBm (250 mW) or 11 dBm + 10 log B, whichever is lower (B= 20-dBi emission BW)</td>
<td>30 dBm (1 W)</td>
</tr>
<tr>
<td>Max EIRP</td>
<td>4 W (30 dBm) with 6 dBi antenna</td>
<td>20 W (53 dBm) for fixed P-I-P application with 23 dBi antenna</td>
<td>1 W (30 dBm) with 6 dBi antenna</td>
<td>4 W (30 dBm) with 6 dBi antenna</td>
</tr>
<tr>
<td>TX Power Reduction (dB)</td>
<td>&gt; 6 dB</td>
<td>&gt; 23 dB for fixed P-I-P application</td>
<td>&gt; 6 dB</td>
<td>&gt; 5 dB</td>
</tr>
<tr>
<td>Out of Band EIRP, Emission</td>
<td>≤ 27 dBm/MHz outside 5150-5350 MHz</td>
<td>≤ 27 dBm/MHz outside 5470-5725 MHz</td>
<td>≤ 17 dBm/MHz within 5715-5725 MHz and ≤ 5800-5850 MHz</td>
<td>≤ 27 dBm/MHz outside 5715-5850 MHz</td>
</tr>
<tr>
<td>Max Conducted Power Spectral Density (PSD)</td>
<td>17 dBm/MHz for master device</td>
<td>11 dBm/MHz for mobile/portable client device</td>
<td>11 dBm/MHz</td>
<td>30 dBm/500 kHz</td>
</tr>
<tr>
<td>Dynamic Frequency Selection (DFS) required?</td>
<td>NO</td>
<td>YES, for master devices with detection threshold of -34 dBm for 200 mW (23 dBm) Operating EIRP ≤ 1 W (30 dBm). Devices must sense for radar signals at 100% of its emission BW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmit Power Control (TPC) required?</td>
<td>NO</td>
<td>YES, if Max EIRP ≤ 500 mW (27 dBm) and able to lower EIRP below 24 dBm</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Minimum BW requirement</td>
<td>N/A</td>
<td>6-dB BW = 500 kHz</td>
<td>6-dB BW = 500 kHz</td>
<td>6-dB BW = 500 kHz</td>
</tr>
</tbody>
</table>
The 5 GHz band is increasingly being used for WiFi, since this band is less congested than the 2.4 GHz band. Currently, three Wi-Fi standards operate in the 5 GHz band, including the new 802.11ac.

802.11a operates in the 5 GHz band and allows throughput of up to 54 Mbps. 802.11n operates on both 2.4 and 5 GHz bands and it allows achieving maximum theoretical data rates of 600 Mbps using up to four MIMO streams. 802.11ac is a new Wi-Fi standard that allows having a higher throughput in the 5 GHz band. With this standard, approved in January 2014, it is expected to achieve throughputs of at least 1 Gbps in a multi-station WLAN configuration and at least 500 Mbps in a single link. In order to accomplish these data rates, it requires higher transmission frequency bandwidths of 80 MHz and up to 160 MHz, as well as different technical improvements, such as higher order modulations (it uses 256-QAM), an increased number of MIMO spatial streams (up to eight) and downlink multi-user MIMO.

The 5 GHz band is also being proposed for LTE-U (LTE-Unlicensed). LTE-U will deliver LTE using initially unlicensed 5 GHz spectrum [6]. LTE-U offers mobility at much faster speeds and high efficiency and it allows Carrier Aggregation (CA) and Supplemental Downlink (SDL), both of which help the integration of these unlicensed bands and LTE. CA and SDL permit a higher downlink bandwidth for the benefit of the users. LTE-U will make it possible to achieve higher data rates using both licensed and unlicensed bands, while keeping the network and service reliable and robust for mobility.

As noted, 802.11a, 802.11n, 802.11ac and LTE-U base their implementation on the use of the 5 GHz band, which is not being fully exploited. However, the 5 GHz band is allocated on a primary basis for operations related to different uses, depending on the frequency range. The 5 GHz incumbent uses are indicated in Figure 2.2 and they include MSS (Mobile Satellite
Services), Aeronautical Radionavigation Services (ARNS), Fixed Satellite Services (FSS) (Earth-to–space), Earth Exploration Satellites, UAS (Unmanned Aircraft Systems), Radiolocation Services, Maritime Radionavigation Services and Meteorological Radars [7]. In order to protect these communications from harmful interference of unlicensed users, commercial equipment has to be certified for their operation and should incorporate interference mitigation techniques, such as Transmit Power Control (TCP) and Dynamic Frequency Selection (DFS).

DFS is a radar detection mechanism that switches the transmitting frequency to another channel if it detects the presence of radar signals or goes into sleep mode if no other channel is available [7]. This mechanism should be used, for example, by equipment that use the same frequency band as the Terminal Doppler Weather Radars (TDWR). TDWR are meteorological radars that operate in the 5.250-5.350 GHz and 5.470-5.725 GHz frequency ranges.
Figure 2.2. 5 GHz incumbent uses
2.2 Radio propagation

This section presents theoretical background on radio propagation concepts that are used in this work.

2.2.1 Radio propagation mechanisms

In wireless communications, radio propagation is characterized by three basic propagation mechanisms: reflection, diffraction and scattering of the signal.

Reflection is produced when the electromagnetic wave has contact with a surface that is relatively large compared to the wavelength of the propagating signal. They are generally flat surfaces, like buildings, the earth surface, walls, ceilings, floors [1].

Diffraction occurs when the radio path between transmitter and receiver is obstructed by a large surface with sharp edges. It generates secondary waves that cause the signals to bend around the obstacles, even in NLOS conditions [1].

Scattering occurs when the wave encounters objects that have size relatively small compared to the wavelength of the signal and the number of obstacles is large. It can be produced by foliage, rough or small surfaces or other irregularities in the channel [1].

2.2.2 Free space propagation model

This model predicts the signal received when the path between transmitter and receiver has line-of-sight and is clear and unobstructed. It is applicable to satellite and microwave communications. For a distance \( d \), the received signal power \( P_r \) is determined by the Friis free space equation, indicates in Equation 2.1 [1][8].
\[ P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \]  

Equation 2.1

where \( P_t \) is the transmitted power, \( G_t \) and \( G_r \) are the gains of the transmitting and receiving antennas, \( \lambda \) is the signal wavelength and \( L \) is the system loss factor.

From this equation is it possible to extract the free space path loss \( FSPL \), which indicates the signal attenuation in dB expressed as a difference between the effective transmitted power and the received power. Considering antennas of unity gain, the basic free space path loss is determined by Equation 2.2.

\[ FSPL(dB) = 10 \log \left( \frac{4\pi df}{c} \right)^2 \]  

Equation 2.2

For \( d \) in meters and \( f \) in MHz, it can also be written as in Equation 2.3.

\[ FSPL(dB) = 20 \log_{10}(d) + 20 \log_{10}(f) + 32.45 \]  

Equation 2.3

2.2.3 Indoor propagation models

Indoor propagation is strongly influenced by the distribution of the building, the construction materials and the building type [1][8][9], which makes the propagation in this environment much more complex than in outdoors. Based on measurements performed, some path loss models have been empirically derived in order to predict the path loss as a function of distance. The most representative indoor path loss models are presented in this section.

2.2.3.1 Partition losses (same floor)

Partition losses model account for the partitions or walls that are part of the building [1]. Hard partitions are part of the building structure and are made of metal studs, drywall and,
sometimes, concrete. Soft partitions are usually made of drywall and can be disassembled and reinstalled. Researchers have estimated the path loss exponent $n$, which indicates the rate of change of the path loss with the distance, for different building materials from which the partitions are made, based on previous measurements [10][11][12][13].

### 2.2.3.2 Partition losses between floors

Partition losses between floors are influenced by the construction material used to create the floors, as well as the external dimensions and materials of the building, including the number of windows. Similarly, previous measurements have estimated the average floor attenuation factor different buildings [11].

### 2.2.3.3 Log-distance path loss model

The log-distance path loss model for a distance $d$ is indicated in Equation 2.4 [1].

$$
\overline{PL}(dB) = \overline{PL}(d_0) + 10n \log \left( \frac{d}{d_0} \right)
$$

Equation 2.4

Where $n$ is the path loss exponent, $d_0$ is a reference distance close to the transmitter and $\overline{PL}(d_0)$ is the path loss measured at this reference distance.

### 2.2.3.4 Log-distance shadowing model

The log-normal shadowing model considers the shadowing effects that occur when there are different levels of clutter along the propagation path [1]. At a specific separation between
transmitter and receiver, the signal has a Gaussian distribution around the distance-dependent mean, which is denoted by Equation 2.5.

$$PL(d)[dB] = \bar{PL}(d) + X_\sigma = \bar{PL}(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma \quad \text{Equation 2.5}$$

2.2.3.5 Attenuation factor model

This model was formulated by Seidel and Rappaport for 914 MHz and is described by Equation 2.6 [11]:

$$\bar{PL}(d)[dB] = \bar{PL}(d_0)[dB] + 10n_{FS} \log\left(\frac{d}{d_0}\right) + FAF[dB] + \sum PAF[dB] \quad \text{Equation 2.6}$$

This equation permits to estimate a relative path loss for a distance \( d \) from the transmitter, considering a reference path loss calculated at a distance \( d_0 \). The parameter \( n_{FS} \) indicates the path loss exponent in the same floor. FAF (Floor Attenuation Factor) indicates the floor attenuation factor for a specific number of floors and PAF (Partition Attenuation Factor) represents the partition attenuation factor for a specific obstruction along the 3D ray drawn between transmitter and receiver [1]. Primary ray tracing consists on drawing a single ray between transmitter and receiver.

Equation 2.7 shows an alternative path loss model in which the parameter \( n_{MF} \) denotes the path loss exponent calculated based on measurements through multiple floors.

$$\bar{PL}(d)[dB] = \bar{PL}(d_0)[dB] + 10n_{MF} \log\left(\frac{d}{d_0}\right) + \sum PAF[dB] \quad \text{Equation 2.7}$$
2.2.3.6 IEEE 802.11 ax channel model

IEEE 802.11ax will be a new wireless standard that is expected to be the successor of 802.11ac. It will increase the efficiency of WLAN networks and it will work in both the 2.4 and 5 GHz bands.

Indoor path loss models proposed for 802.11ax are the same than the ones used in 802.11n [14]. The overall indoor path loss $PL_{\text{indoor}}$, in dB, is described in Equation 2.8 [15]:

$$PL_{\text{overall}} = PL_{\text{indoor}}(d) + PEL_{\text{floor}} + PEL_{\text{wall}}$$  \hspace{1cm} \text{Equation 2.8}

where $PEL_{\text{floor}}$ and $PEL_{\text{wall}}$ are the extra floor penetration loss and wall penetration loss, respectively.

The indoor path loss for a distance $d$ from the transmitter is indicated in Equation 2.9 and it considers a breakpoint distance $d_{BP}$, in which the propagation conditions change [15]. $L_{FS}(d)$ is the free space path loss for a distance $d$.

$$PL_{\text{indoor}}(d) = \begin{cases} L_{FS}(d) & , d \leq d_{BP} \\ L_{FS}(d) + 35\log(d/d_{BP}) & , d \geq d_{BP} \end{cases}$$  \hspace{1cm} \text{Equation 2.9}

The path loss parameters for indoor residential and a typical office building are indicated in Table 2.1. Up to the breakpoint distance, the path loss consists of the free space path loss with slope 2 and, after this breakpoint, the slope is 3.5. The breakpoint varies according to the channel model. The table also includes information about the standard deviation of log-normal shadow fading.
Table 2.1. Path loss model parameters [15]

<table>
<thead>
<tr>
<th>Channel Model</th>
<th>$d_{BP}$ (m)</th>
<th>Slope before $d_{BP}$</th>
<th>Slope after $d_{BP}$</th>
<th>Shadow fading std. dev. (dB) before $d_{BP}$ (LOS)</th>
<th>Shadow fading std. dev. (dB) after $d_{BP}$ (NLOS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor residential</td>
<td>5</td>
<td>2</td>
<td>3.5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Indoor typical office</td>
<td>10</td>
<td>2</td>
<td>3.5</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

The indoor floor penetration loss depends on the floor separation between transmitter and receiver and it is calculated using Equation 2.10, where $n$ is the number of floors penetrated [15].

$$ PEL_{floor} = 18.3n^{((n+2)/(n+1)) - 0.46} $$

Equation 2.10

Internal wall penetration is estimated using Equation 2.11, where $m$ is the number of walls penetrated and $L_{iw}$ is the penetration loss for a single wall.

$$ PEL_{wall} = m * L_{iw} $$

Equation 2.11

In the case of outdoor to indoor scenarios, the path loss can be calculated using Equation 2.12:

$$ PL_{outdoor-to-indoor} = PL_{outdoor-NLOS}(d_{out} + d_{in}) + 20 + 0.5d_{in} $$

Equation 2.12

where $d_{out}$ is the outdoor distance and $d_{in}$ is the indoor distance. 20 is the building penetration loss in dB. $PL_{outdoor-NLOS}(d)$ is the path loss in outdoor non-line-of-sight conditions, which can be calculated according to Equation 2.13.

$$ PL_{outdoor-NLOS}(d) = 36.7 \log 10(d) + 22.7 + 26 \log 10(f_c), 10m \leq d \leq 2km $$

Equation 2.13

where $d$ is the distance in meters between transmitter and receiver and $f_c$ is the carrier frequency in GHz.
2.2.4 Doppler shift

The Doppler frequency shift is caused by the relative movement between transmitter and receiver or due to scattering in the environment. **Figure 2.3** shows an illustration of the Doppler effect. The source S is located remotely from receiver moving at a constant velocity $v$ between points X and Y, which are separated by a distance $d$. $\Delta l$ is the difference in the path length travelled by the signal from source S to the mobile at points X and Y and $\Delta t$ required by the receiver to travel between those points [1][8].

![Doppler effect diagram](image)

**Figure 2.3.** Doppler effect

The phase change at the receiver is described by Equation 2.14.

$$\Delta \phi = \frac{2\pi \Delta l}{\lambda} = \frac{2\pi v \Delta t}{\lambda} \cos \theta$$  \hspace{1cm} \text{Equation 2.14}

The Doppler frequency shift $f_d$ is determined by Equation 2.15.

$$f_d = \frac{1}{2\pi} \frac{\Delta \phi}{\Delta t} = \frac{v}{\lambda} \cos \theta$$  \hspace{1cm} \text{Equation 2.15}

2.2.5 Small-scale fading and multipath

The received signal level is determined by three factors: path loss, shadowing and multipath. Path loss depends on the distance between transmitter and receiver. Shadowing is
originated by large obstacles along the propagation path and it causes large-scale fading. Multipath is caused by scattering of the radio signals in the environment, which causes the signal to have constructive or destructive interference, depending if the signal components arrive to the receiver in phase or out of phase, producing an additive or subtractive effect, respectively. The signal components reach the receiving antenna by two or more different paths, due to different phenomena, small obstacles or irregularities in the channel [8][9]. It produces small-scale fading.

2.2.5.1 Multipath channel parameters

The time and frequency varying characteristics of a multipath channel can be described through four parameters: Doppler spread, coherence time, delay spread and coherence bandwidth.

Doppler spread and coherence time are parameters that describe the time varying nature of the channel. The Doppler spread $B_d$ measures the spectral broadening of the channel caused by the relative movement of the transmitter and the multipath effects in the channel. Coherence time $T_c$ is the inverse of the Doppler spread and it indicates the time over which the channel impulse response is invariant. It is a measure of the frequency dispersiveness of the channel in the time domain [1].

Delay spread and coherence bandwidth describe the frequency varying nature of the channel. The delay spread $T_s$ is a multipath channel parameter that can be determined from a power delay profile [1]. This delay is measured relative to the first detectable signal that arrives at the receiver and is defined as the difference in propagation time between the longest and shortest path, considering only the paths with significant energy [3]. The coherence bandwidth is
inversely proportional to the delay spread and it measures the range of frequencies over which
the channel can be considered flat, so the frequency components are correlated in amplitude [1].

**2.2.5.2 Types of small-scale fading**

Based on multipath time delay spread, small-scale fading can be classified as either flat
fading or frequency selective fading. Flat fading occurs when the coherence bandwidth of the
channel is higher than the signal bandwidth. Otherwise, the signal will be have frequency
selective fading [1].

Considering the Doppler spread of the channel, the small-scale fading can be classified in
fast fading and slow fading. Fast fading occurs when the channel impulse response changes
faster than the baseband signal variations. Otherwise, the signal will experience slow fading [1].

**2.2.5.3 Rayleigh and Rician distributions**

Fast fading can be characterized using different mathematical distributions.

Rayleigh fading is used when there is no line-of-sight between transmitter and receiver.
The probability density function is described by Equation 2.16 [1][9].

\[
p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right), & (0 \leq r < \infty) \\ 0, & (r < 0) \end{cases} \quad \text{Equation 2.16}
\]

The parameter \(\sigma\) indicates the rms value of the received voltage signal before envelope
detection [1].

Rician fading, is used when there is line-of-sight path between transmitter and receiver.
One of the components of the received is much stronger that the others, which typically
corresponds to the line-of-sight component of the signal. The probability density function is described by Equation 2.17 [1][8][9].

\[
p(r) = \begin{cases} 
\frac{r}{\sigma^2} \exp \left( -\frac{(r^2 + A^2)}{2\sigma^2} \right) I_0 \left( \frac{Ar}{\sigma^2} \right), & (A \geq 0, r \geq 0) \\
0, & (r < 0)
\end{cases}
\]

Equation 2.17

The parameter A indicates the peak amplitude of the dominant signal component and \( I_0 (\bullet) \) is the modified Bessel function of the first kind and zero-order. The Rician distribution can be described in terms of the k-factor, which is defined in Equation 2.18. The Rician k-factor determines the ratio between the specular signal component and the variance of the multipath [1].

\[
k = \frac{A^2}{2\sigma^2}
\]

Equation 2.18

When there is no dominant line-of-sight component, the k-factor becomes 0 and the Rician distribution becomes a Rayleigh distribution.

2.2.5.4 Multipath models

Several models have been proposed in order to explain the statistical nature of a multipath fading channel.

Clarke’s model is a multipath model for flat fading that is based on isotropic scattering. It considers a fixed transmitter and a receiver moving at a velocity \( v \) in the x-direction, as shown in Figure 2.4. It assumes that \( N \) azimuthal plane waves arrive at the receiver, with equal average amplitudes and random phases and angles of arrival. The angles are measured in the x-y plane with respect to the direction of motion. The E-field \( E_z (t) \) can be expressed as in Equation 2.19:
\[ E_z(t) = T_c(t) \cos(2\pi f_c t) - T_s(t) \sin(2\pi f_s t) \quad \text{Equation 2.19} \]

\( T_c(t) \) and \( T_s(t) \) are the in-phase and quadrature components of the received signal [16]. Both parameters are uncorrelated zero-mean Gaussian random processes. The envelope of the received E-field can be calculated using Equation 2.20 and it has a Rayleigh distribution given by Equation 2.16 [1].

\[ |E_z(t)| = \sqrt{T_c^2(t) + T_s^2(t)} = r(t) \quad \text{Equation 2.20} \]

\[ F i g u r e \ 2.4. \ P l a n e \ w a v e \ a r r i v i n g \ a t \ a r b i t r a r y \ a n g l e s \ i n \ t h e \ x-y \ u s e d \ t o \ d e s c r i b e \ C l a r k e ’ s \ m o d e l \ [1] \]

Gans incorporated the spectrum analysis for Clarke’s model. He included the Doppler shift in the channel model by passing the envelope \( r(t) \) through the filter \( s(t) \). For an angle of arrival \( \alpha \) and considering a vertical \( \lambda/4 \) antenna with azimuthal gain \( G(\alpha) = 1.5 \) and uniform distribution \( p(\alpha) = 1/2\pi \) over 0 to \( 2\pi \), the power spectrum of the electric field can be described by Equation 2.21 [1]:

21
\[ S_{E_c}(f) = \frac{1.5}{\pi f_m \sqrt{1 - \left( \frac{f - f_c}{f_m} \right)^2}} \]  

Equation 2.21

where \( f_c \) is the carrier frequency of the CW signal, \( f_m \) is the maximum Doppler shift and \( f \) is the frequency ranging from \( f_c - f_m \) to \( f_c + f_m \).

**Figure 2.5** shows the power spectral density of the carrier signal due to Doppler fading.

![Doppler power spectrum of a CW carrier considering Gans model](image)

**Figure 2.5.** Doppler power spectrum of a CW carrier considering Gans model [1]

Aulin’s model [17] is a generalization of Clarke’s model considering that the scattering waves do not travel horizontally, but in a three-dimensional space. It is basically a 3D statistical modification of the scattering distribution that includes a \( \beta \) angle, which in Clarke’s model is always zero. Its representation is shown in **Figure 2.6.** With this consideration, the power spectrum of the envelope is significantly affected and becomes smoother and finite, compared to the one obtained in Clarke’s model. The probability density function of the signal envelope is not affected.
Aulin’s model has proved to be more consistent with previous measured spectra. The probability density function of the angle $\beta$ is defined by Equation 2.22.

$$p(\beta) = \begin{cases} \frac{\cos \beta}{2 \sin \beta_m} & |\beta| \leq |\beta_m| \leq \frac{\pi}{2} \\ 0 & \text{elsewhere} \end{cases}$$  

Equation 2.22

**Figure 2.6.** 3D geometry of statistical multipath model using Aulin’s model [18]

Parsons [8] provides a similar form for the probability density function of the angle $\beta$, but using a cosine form, as indicated in Equation 2.23.

$$p(\beta) = \begin{cases} \frac{\pi}{4|\beta_m|} \cos \left( \frac{\pi}{2} \frac{\beta}{\beta_m} \right) & |\beta| \leq |\beta_m| \leq \frac{\pi}{2} \\ 0 & \text{elsewhere} \end{cases}$$  

Equation 2.23

**Figure 2.7** shows the form of the Doppler spectrum using a two-dimensional Clarke’s model and three-dimensional Aulin’s and Parsons’ models. All the spectra are bandlimited to $|f| \leq f_m$. Parsons’ model avoids the discontinuity at the edge in Clarke’s model and the constant
value for $f_m \cos \beta_m \leq |f| \leq f_m$ obtained in Aulin’s spectrum, which does not fit the real measurements [19].

![Graph showing Doppler spectrum](image)

**Figure 2.7.** Theoretical Doppler spectrum using different scattering models [8]

### 2.3 Small-scale multipath measurements

Wideband channel sounding techniques permit measuring the small-scale multipath and can be classified in three categories, which are described in the following paragraphs.

A direct RF pulse system consists of a wideband pulsed bistatic radar that transmits repetitive pulses of width $T_{bb}$. The signal is amplified and then detected in the receiver through an envelope detector. The receiver has a wide bandpass filter of $BW = 2/T_{bb}$ [1]. This system measures the power delay profile of the channel. The advantage is its low complexity, but the main inconvenience is that it is subject to interference and noise due to the wide bandwidth of the bandpass filter.

Another measurement system is the spread spectrum sliding correlator channel sounder. The transmitter can be wideband and the receiver is narrowband preceded by a wideband mixer,
which improves the dynamic range of the system [1]. The carrier signal is mixed with a binary pseudo-noise (PN) sequence, which causes the transmitted signal to have a large bandwidth. The signal has a chip duration of $T_c$ and a chip rate of $1/T_c$ Hz. At the receiver, the signal is detected by mixing the spread spectrum signal with the same PN sequence using a clock slightly slower than the transmitter chip clock. This method is called sliding correlator and permits rejecting passband interference.

A stepped-frequency channel sounder permits to measure the channel impulse response in the frequency domain [1]. It consists of a vector network analyzer which controls a swept frequency oscillator. The frequency response of the channel is monitored through an S-parameter test set. It scans a certain frequency band by stepping through different discrete frequencies. This method indirectly provides magnitude and phase information in the time domain, but requires synchronization between transmitter and receiver. For this reason it is more useful in static configurations in indoor environments.

2.4 Previous measurements in 5 GHz

In the past, due to their widely spread use, the majority of the propagation studies have been performed in 800, 900, 1300, 1900 and 2400 MHz bands [1]. They were focused on characterizing the path loss, since it is one of the main parameters to be considered in the design of wireless networks, and some of them also studied the delay spread. In 1990, Devasirvatham et al. [20] compared the time delay spread and signal levels measurements for 850 MHz, 1.7 GHz and 4 GHz in office buildings. In 1991, Rappaport [10] described the path loss characteristics in different buildings measured at 1300 MHz. In 1992, Seidel and Rappaport [11] developed path
loss prediction models for multifloor buildings in 914 MHz. In the same year, Seidel et al. [12] performed path loss and delay spread measurements in office buildings at 915 and 1900 MHz. In 1993, Andersen et al. [13] characterized the path loss and multipath delay spread for different buildings in 900, 914, 1300, 1500, 1900 and 4000 MHz.

Research on 5 GHz mobile channels have also been performed before. The measurements were based on collecting the magnitude and phase of the signals and, from them, estimating the channel parameters. Some of the most significant studies are described in the next paragraph.

In 2001, Kivinen et al. characterized the LOS and NLOS path loss and delay spread for wideband indoor radio channels in 5.3 GHz [21]. In 2002, Cheung and Prettie compared the path loss between 5 GHz U-NII bands and the 2.4 GHz ISM band for LOS and NLOS conditions. In 2002, Chung and Bertoni [22] estimated the path loss and the delay spread in office buildings and residential environments. They performed measurements of continuous wave propagation using a spectrum analyzer in 5.2 GHz and swept frequency measurements in the range from 5.15 GHz to 5.35 GHz. In 2007, Xu et al. [23] studied the indoor LOS and NLOS path loss parameters for office buildings in 5.25 GHz considering different empirical path loss models.

The instrumentation used did not permit to extract the in-phase and quadrature components of the received signal, which would enable to estimate the Doppler power spectral density in order to perform a detailed analysis of the scattering environment. In this context, this research will study the propagation characteristics in the 5 GHz band for indoor and indoor to outdoor scenarios for mobile channels. For this purpose, we will use the novel narrowband measurement equipment developed at NTIA/ITS, which consists of a fixed transmitter and a mobile receiver that collects in-phase and quadrature baseband signals for later processing.
This is the reason why this novel measurement system offers a clear advantage over the channel sounders described in the previous section and it constitutes a powerful tool for further propagation and interference studies, which will be fundamental for evaluating new technologies and their coexistence with previous services.

Additionally, because of the recent modifications introduced by the FCC, it is necessary to perform further studies in order to characterize the channel considering its current uses and future applications, including spectrum sharing techniques, especially in urban environments, which represent common scenarios in which these new technologies will be used.
CHAPTER 3

3 MEASUREMENT SYSTEM AND EXPERIMENTAL PROCEDURE

This chapter describes the measurement setup, calibration and methodology used in this work, as well as the data processing techniques for the estimation of the path loss, Doppler power spectrum and fading statistics in this band.

3.1 Measurement system

A continuous wave (CW) novel measurement system for studying mobile radio channels has been developed at NTIA/ITS [24]. The system is a narrowband channel sounder [25] [26], which consists of a CW transmitter and a receiver. The receiver is based on a vector signal analyzer (VSA) and it incorporates highly stable oscillators that permit the post-processing of baseband complex signals with sufficient accuracy to observe Doppler based channel characteristics. The block diagram of this system is shown in Figure 3.1.

![Figure 3.1. Block diagram of the fixed-to-mobile propagation measurement system](image)

Figure 3.1. Block diagram of the fixed-to-mobile propagation measurement system
3.1.1 Transmitter

During measurements, the transmitter is set in a fixed location. It consists of a frequency synthesizer stabilized by a 10 MHz rubidium clock, a RF power amplifier and an 8 dBi omnidirectional antenna [24]. The rubidium clock has a nominal accuracy of one part in $10^{12}$ and it provides a precise and highly stable transmitted frequency that allows measuring the Doppler effects. With this reference, the frequency synthesizer generates a 5.41 GHz CW signal at a power level of 10 dBm. In case the received power is below the noise floor, which will depend on the different scenarios of measurement, we can transmit at 0 dBm and add a 30 dB gain RF power amplifier that will boost the transmitting output power to 30 dBm. The transmit signal is fed an omnidirectional antenna and transmitted.

Figure 3.2.a) shows a picture of the transmitter system. It contains a frequency synthesizer (a.1), a 10 MHz rubidium clock (a.2) and its power source (a.3), a RF power amplifier (a.4) and its power source (a.5) and a transmitting omnidirectional antenna (a.6). A power meter (a.7) is also used for estimating the cable loss in the transmitter and receiver systems.

3.1.2 Receiver

The main component of the mobile receiver system is the Agilent N9030A PXA Signal Analyzer, which operates in the frequency range from 3 to 50 GHz and runs as a Vector Signal Analyzer (VSA). The other components of the receiver system are a 10 MHz rubidium clock, an omnidirectional 8 dBi antenna and an UPS (Uninterruptible Power Supply) [24]. The VSA is the data acquisition system and it digitizes the analog signal received by the 8 dBi antenna and
down-converts it to a discrete time series of baseband in-phase (I) and quadrature (Q) components. The VSA is set to a receiving frequency of 5.41 GHz and is disciplined using the rubidium clock, which permits the transmitter and receiver systems to operate at exactly the same frequency and in a stable fashion during the course of a measurement. The transmitter and receiver are sufficiently stable so that it is possible to extract the Doppler frequency shift between the fixed transmitter and the mobile receiver. The UPS is used for powering the mobile receiver system and provides autonomy of approximately 1 hour.

**Figure 3.2.b** shows the details of the receiver system. It shows a VSA (b.1), a 10 MHz rubidium clock (b.2), an 8 dBi omnidirectional antenna (b.3) and an UPS (b.4)

### 3.1.3 Advantages of the measurement system

This novel mobile propagation measurement system has several advantages. It uses the VSA as the data acquisition system, which extracts the real and imaginary components of the received signals that provide Doppler information of the mobile channel. Therefore, it makes possible to understand how the signals are scattered within, into or out of buildings and perform detailed propagation and interference studies. This information cannot be obtained from traditional measurement equipment used in the cellular industry, which relies on spectrum analyzers and scanners for determining basically the path loss, based on just the signal magnitude.

The measurement system is precise and accurate, since it uses highly stable oscillators, which enables the signals that are transmitted and received at exactly the same frequency. Because of channel effects, the phase of the received signal will change and the VSA will provide accurate information of the Doppler shifts. In this way, the system makes it possible to
perform detailed and precise propagation and interference studies. The results obtained will be helpful for estimating the characteristics of 5 GHz radio mobile channels in modern urban environments.

Furthermore, since it is a narrowband system, it transmits a CW signal and the receiver system performs a spatial scanning based on a moving probe through a static field structure. This is in contrast to a broadband system, which uses a static probe in which the field structure is changed using frequency scanning. A broadband system needs a higher bandwidth of clear spectrum and a proportionally higher sampling rate, which requires more processing in the computer [26]. Another advantage of a narrowband system is that it requires a small amount of spectrum available for the measurements, which makes it easier to find quiet channels in the 5GHz band. Consequently, the use of a narrowband system permits accurate measurements with less complexity and without the need of additional bandwidth and higher sample rates that a broadband system requires.

A mobile version of this system has been used before for studying mobile propagation in the 430 MHz band in an outdoor environment in Boulder [24]. A residential area was chosen for the measurements, the transmitter was fixed on top of a building and the receiving was installed in a van moving at a constant velocity.
3.2 System configuration

For our measurements, the VSA bandwidth is set to 1 kHz, which permits sufficient frequency resolution for determining the Doppler shifts, which are less than 50 Hz for the walking speed at which the receiver is moved. The bandwidth selected includes positive and
negatives frequencies and, therefore, the received signal will be sampled by the VSA at a sampling frequency of 1280 Hz, which provides adequate sampling well in excess of the Nyquist rate.

The system is set at an operating frequency of 5.41 GHz and both, the transmitter and receiver, use a 10 MHz frequency reference for stability and accuracy of the I and Q data measurements [25]. The process for synchronizing the phases of the rubidium clocks is performed by adjusting the control voltage of the rubidium clock used to discipline the frequency synthesizer in the transmitter. The receiver uses a rubidium clock with a built-in power source that it is not adjustable. In order to synchronize the phases, the transmitter and receiver must be turned on and placed one facing each other in line of sight conditions. On the VSA, we look at the I-Q magnitude and phase plot. When the frequencies are matched, the polar plot should be as stable as possible and not rotating in any specific direction. This calibration is performed before each measurement and sets both oscillators at the same frequency and phase.

It is also required to set the range and maximum displayed amplitude of the received signal that the VSA will collect. The setting will depend on the measurement scenario and the signal levels received along the route.

Figure 3.3 presents the VSA display that is used for the phase calibration process. The upper plot shows the instantaneous frequency spectrum of the signal in logarithmic scale, used for setting the range and maximum display amplitude, and the lower graph shows the I-Q phase plot used for calibrating the phase of the clocks.
3.3 Measurement location

The measurements are performed in the Discovery Learning Center building (DLC), on the campus of the University of Colorado at Boulder. The building, which is shown in Figure 3.4, is located next to the Engineering Center and is a modern research facility for engineering students. It was built in 2002 and has 4 floors: level 2B (the actual basement), level 1B (ground floor), level 1 and level 2. The approximate north-south length is 42 meters and the west-east length is 27 m.

This building was selected because its structure is representative of a typical multi-floor modern office building and the objective is to replicate the conditions expected in this environment. The detailed description of each scenario considered in the measurements is indicated in Chapter 4.
Figure 3.4. External views of the DLC: a) south end of the DLC and b) east end of the DLC
3.4 Research methodology

It was necessary to establish a specific operating frequency for the measurements. For that purpose, we did a spectrum survey around the DLC using a spectrum analyzer and we noticed that the 5 GHz U-NII bands are heavily used for WiFi in all floors. For this reason, we decided to set 5.41 GHz as the operating frequency, since it is not used and, therefore, we will not interfere or be interfered. Note that the maximum transmitting power used for the measurements is 30 dBm (1W).

The measurements were performed during the winter break, between January 6th and 8th, since not many people were in the DLC during those days. In this way, their presence had minimal affect the channel statistics and fading characteristics and, therefore, it was possible to obtain results that approximate better to the theoretical models.

The path followed in each measurement scenario is not a straight line, but a combination of straight sections and turns in a loop or U-shape. The reason is because the DLC is not long enough to acquire enough data for studying the mobile radio channel parameters in an extensive way. In order to collect the data, the receiving system was installed in a cart and pushed at a constant walking velocity of approximately 3 km/h along the path.

For each scenario, the VSA was configured for acquiring data during the time that it approximately takes to walk the whole path, considering the stop intervals and turning points, at a speed of approximately 3 km/h. This transmit time was previously determined and used as the acquisition time when configuring the VSA. This time included additional seconds for recording noise when the transmitter is off, in order to measure the noise floor of the system and confirm that unexpected transmitters had not appeared in the band. It should be noted that the VSA does
not allow monitoring the received signal while data is acquired so it is not possible to see in real
time how the signal varies along the path, detect possible on-channel overloading or interference.
The data recorded in the VSA is saved as a .mat file for later processing in MATLAB.

In order to start the measurements, the transmitter and receiver systems should be
configured and the phase calibration procedure should be done every time that transmitter and/or
the receiver is turned on, so it will produce accurate Doppler shifts measurements. Then the
transmitter is placed in a specific location and the receiver is moved along the path. The same
procedure is applicable for each scenario.

3.5 Waypoint navigation method

A waypoint navigation method was used to estimate the relative position of the receiver
with respect to the transmitter in order to study how the propagation parameters vary along the
receiver path. The transmitter was fixed in a certain location inside the DLC and the receiver was
assumed to be moved at a constant walking velocity of 3 km/h. The velocity was monitored by
means of a speedometer installed on the cart. The start and stop points for each straight section
were marked on the floor in the DLC in order to measure the distance for each section and for
repeatability of the measurements.

We performed an interpolation in order to estimate the geolocated position of the receiver
along the path, considering the measured distance for each section and assuming a constant
walking velocity of 3 km/h. At the end of each of straight section, we stopped the cart in order to
easily identify this position, characterized by reduced Doppler spreading and little variability of
the signal envelope. After stopping the cart, we made a turn and then continued pushing it along the next straight section until completing the whole path for the scenario measured.

The stops, turning points and sections where no signal is transmitted are easily identified and removed from the received signal in order to calculate the propagation parameters. The stop points can be easily identified by plotting the normalized received signal, as shown in Figure 3.5. The sections where the amplitude keeps approximately constant indicate the intervals when the receiver is not moving. In these stop points there is minimal fast fading since there is no relative movement between transmitter and receiver. This can also be seen in a Doppler power spectrum plot, which shows that, during the stop times, the Doppler frequency shift is approximately zero. The final section in the normalized received signal plot corresponds to the interval when the transmitter is off and the receiver does not move in order to record the noise and calculate the noise floor. The noise power is low, but it has variable random amplitude, which can be noticed in the normalized plot.

The geolocation method permits to establish a XYZ coordinate system in order to estimate the relative distance between transmitter and receiver, which is moved along level 1B, level 1, level 2 and around the DLC.
Figure 3.5. Normalized received signal.

3.6 Data processing

The software used for post-processing the data is MATLAB since it offers a powerful computing environment with many statistical functions and toolboxes useful in communications analysis.

The output of the VSA is the complex baseband time series \( s[n] = I[n] + jQ[n] \), where \( I[n] \) and \( Q[n] \) are, respectively, the in-phase and quadrature components of the received baseband signal. The envelope \( |s[n]| \) is calculated as \( |s[n]| = \sqrt{I[n]^2 + Q[n]^2} \). In order to have an accurate calculation of the radio channel parameters, only the time intervals when the receiver is
moving should be considered. The stop and turning points should be removed, as well as the time
sections when no signal is transmitted.

From the data it is possible to calculate the Path Loss and the Power Spectral Density and
estimate the best fit Probability Density Function (PDF) of the fading distribution. Figure 3.6
shows general block diagrams of the procedure to post-process the data in order to calculate the
channel parameters relevant to this work.

\[
\text{VSA output: } s[n] = I[n] + jQ[n] \\
\text{Envelope: } |s[n]| \\
|s[n]| \text{ demeaning} \\
\text{Path Loss} \\
\text{PDF estimation of the distribution fitting} \\
\text{Doppler Power Spectral Density (PSD)}
\]

**Figure 3.6.** Block diagrams of the data post-processing procedure

The data acquired is used for estimating the following channel parameters for each
scenario:

### 3.6.1 Path loss

In order to plot the path loss vs. distance, the data processing will be based on the
envelope of the received signal, considering only the times when the receiver is moving. The
path loss is determined by the distance between transmitter and receiver and is affected by the
structure of the building and shadowing effects caused by obstructing objects on the propagation
path. The instantaneous path loss also presents the effect of multipath, due to signal scattering in the environment.

We will describe and compare how and why the path loss varies along the route for the different scenarios studied. For this purpose, we follow certain steps, which will be detailed in the next paragraphs.

First, in order to minimize the effect of multipath on the path loss and observe primarily the slow changing long-term fading, we need to calculate the running average of the received signal envelope, denoted by $P_{rx}$, based on Lee’s method [27]. This method permits to estimate the spatial local mean values of the received signal along the path. This method states that the local means should be calculated by averaging at least $N$ samples within an averaging length of $2L$, considering a distance $d$ between samples in order to be uncorrelated. Lee stated that the minimum number of samples $N$ taken for each running window $2L$ should be set to 50 and $2L$ should be between $20\lambda$ and $40\lambda$, where $\lambda$ is the wavelength of the signal, in order to obtain 1 dB confidence around the real mean value.

Despite Lee’s method was proposed considering a Rayleigh distribution in an outdoor environment using the UHF band (300 MHz to 3 GHz), we will consider it for our measurements, since it is the local means should not vary too much and this is the method recommended by the International Telecommunication Union (ITU) and the European Radiocommunications Committee (ERC) [28][29].

Since the operating frequency used is 5.41 GHz, $\lambda=0.0555$ meters. In this case, we are considering an averaging length $2L$ of $20\lambda=1.11$ meters. We take $N=50$ samples within this interval and, therefore, the samples are taken at a rate of 45 samples per meter.

Next, we calculate the path loss according to the following link budget formula:
\[ PL = P_{TX} - L_{CCTX} + G_{AntTX} - P_{RX} - L_{CCRX} + G_{AntRX} \]

Where:

- \( PL \) is the basic path loss expressed in dB

- \( P_{TX} \) and \( P_{RX} \) are the transmitted and received power levels in dBm. If the amplifier is used in the transmitter, \( P_{TX} = 30 \) dBm and, otherwise, \( P_{TX} = 10 \) dBm. \( P_{RX} \) is calculated using the running average of the envelope of the received signal.

- \( L_{CCTX} \) and \( L_{CCRX} \) are the power losses due to cables and connectors in the transmitter and receiver, respectively. We measured these losses using the power meter and obtained \( L_{CCTX} = 0.8 \) dB and \( L_{CCRX} = 1.5 \) dB.

- \( G_{AntTX} \) and \( G_{AntRX} \) are the transmitting and receiving antenna gains. We use 8 dBi gain omnidirectional antennas in both cases.

The path loss is calculated for two cases: for each section of the path and for the entire route. In both cases, we consider Lee’s method for obtaining local mean values of the received signal along the path. We generate plots of path loss vs. distance that help understand how and why this parameter varies for each section along the path, which will be related to the distance from the transmitter and obstructing objects. Figure 3.7 shows a plot of the instantaneous path loss (gray color), the path loss per straight section along the path, indicated with different colors, and the free space path loss (color black) for no line-of-sight conditions. The gray lines indicate the high variability of the instantaneous path loss, determined by the effect of small-scale fading, which causes positive and negative excursions of the instantaneous path loss around the local mean. The colored lines are the result of applying a running average and they also indicate the
large-scale fading due to blockage effects caused by the presence of large obstacles along the propagation path.

**Figure 3.7.** Instantaneous path loss, path loss per straight section and free space path loss for NLOS conditions

Finally, we calculate the path loss slope by estimating a linear least-squares regression fit. The formula used for calculating the regression plot is indicated in Equation 3.1, from which we estimate the path loss slope $n$ and the Y-intercept $a$ [30].

$$y = nx + a \quad \text{Equation 3.1}$$

The path loss slope indicates the building structure and the propagation conditions. **Figure 3.8** shows the instantaneous path loss and linear least-squares regression fit for the same
measurement scenario than in Figure 3.7, characterized by NLOS conditions. The path loss slope calculated in this example is 4.48 and the standard deviation is 6.47 dB, which indicates a good fit since the instantaneous path loss does not deviate much from the linear regression fit curve, as shown in the figure.

In case we notice that the path loss plot has two or more distinguishable slopes, we will use a dual or multiple slope plot. This is caused by a change in the propagation condition along the path, for example, a change from LOS to NLOS environment.

**Figure 3.8.** Instantaneous path loss and linear least-squares regression fit for NLOS conditions
3.6.2 Doppler power spectrum

This parameter indicates how much the spectrum is broadened because of the relative movement between the transmitter and receiver and/or the presence of multipath in the channel. In order to calculate this parameter, it is necessary to remove the effect of slow fading caused by the local mean of the signal, which varies according to the distance from the transmitter and due to obstacles along the path. This process, called demeaning [31], extends the period over which the signal remains stationary and leaves the fast fading components caused by multipath. It consists on eliminating the local mean of the signal by dividing each sample by the running average calculated around a window width. It works as a moving average filter and the size of the window should be carefully selected in order to effectively remove the low frequency variations without eliminating high frequency components. We use a window of 1 second which effectively removes the local mean and smooth out the signal.

Next, the demeaned complex baseband signal is used to calculate the Doppler power spectrum. Welch’s method is used for reducing the variance and noise of the FFT estimation of the random process, allowing a better estimate of the power spectrum. The Welch’s method is a non-parametric technique for estimating the power spectrum based on averaging windowed periodograms [32]. It first divides the time series into segments that are allowed to overlap. Each of these segments is windowed and the periodograms are calculated and averaged in order to estimate the power spectrum density. This method is useful when computing a random process, since it reduces the variance of a periodogram calculated using the FFT (Fast Fourier Transform). It is based on the Bartlett’s method, which consists on averaged periodograms, but the advantage is that it uses windows and the segments can overlap, reducing even more the
effect of noise and variance on the signal. In this work, we are using a Hamming window and an overlap of 3 samples, since they provide good frequency resolution for determining the different spectral components in the signal. Figure 3.9 shows a comparison between the raw periodogram (blue line) and the power spectral density calculated using Welch’s method (red line) for a time interval of 3 seconds. Note that the variance and noise of the raw periodogram have been considerably reduced by using Welch’s method, which permits to obtain a smoother power spectral density.

![Power Spectral Density](image)

**Figure 3.9.** Raw periodogram and power spectral density estimated using Welch’s method
Additionally, we plot a joint time-power spectral density graph in order to analyze how the signal is scattered during the path, according to the propagation environment, as shown in Figure 3.10.

![Power spectral density vs. Time](image)

Figure 3.10. Joint time-power spectral density

### 3.6.3 Fading statistics

In order to estimate the fading statistics, we use the demeaned time series calculated based on the envelope of the received signal. We use a 3-second interval of this signal, during which the channel can be considered stationary, and perform a Maximum Likelihood Estimation (MLE) using the MATLAB function implemented in the toolbox. The MLE algorithm enables us
to estimate the parameters of the specific distribution to which we are trying to fit the data. In this case, we are using two distributions that have physical significance in propagation: Rayleigh and Rician, for NLOS and LOS conditions, respectively. For the selected time series, we calculate the goodness of fit of the measured data to each of these distributions. The goodness of fit test permits to quantitatively determine how well the data fits the statistical model. In order to measure this parameter, we use the R-squared (R²) method, also called coefficient of determination, which calculates the square of the correlation coefficient between two vectors. It can take values between 0 and 1, where 1 indicates a perfect fit.

This analysis will also be illustrated by plotting the histogram of the envelope, which is graphically compared to the Rayleigh and Rician Probability Density Functions (PDF) with the estimated parameters obtained from the MLE calculation. An example of this plot is shown in Figure 3.11 and it permits having a graphical representation of how well both distributions fit for the same signal segment.
The calculation of the Rician $k$-factor permits to study the fading statistics of the signal and indicates how scattered it is. The $k$-factor is the ratio of dominant to scattered signal powers. Theoretically, for a non-line-of-sight condition, the probability density function (PDF) of the signal envelope follows a Rayleigh distribution if $k$-factor=0 [1][8]. However, in a real world environment, the signal might not get perfectly scattered because of the building structure and objects in the propagation path. The value of the $k$-factor depends on the time during which the signal is evaluated. In this work, we are considering an interval of 3 seconds, during which the channel can be considered stationary. With this consideration, we are setting a referential $k$-
factor threshold, which states that the signal experiences Rayleigh-like fading if \( k \)-factor \( \leq 0.5 \) and, otherwise, the PDF is considered to have a Rician distribution.

Figure 3.12 shows an example of the plot of the Rician \( k \)-factor vs. time along the receiver path in scenario 1. In open outdoor environments with line of sight, the \( k \)-factor has very high values because the signal comes from only one direction. However, for indoor conditions, the \( k \)-factor is low because the signal is affected by reflection, diffraction, scattering and shadowing. The lower the \( k \)-factor, the more scattered the signal is in that particular section and the fading distribution will be more Rayleigh-like.

![K-factor vs. time](image.png)

Figure 3.12. \( k \)-factor vs. time along the receiver path in scenario 1
CHAPTER 4

4 RESULTS

The aim of the measurements is to characterize the 5 GHz mobile radio channel for indoor to indoor and indoor to outdoor propagation. Radio propagation in these environments is much more complex than in outdoor conditions and it is determined by the geometry and distribution of the building and rooms, as well as the construction materials used for the internal and external walls and floors [8]. In mobile indoor environments, the propagation is dominated by multipath fading, due to the relative movement between the transmitter and the receiver, as well as the effect of reflection, diffraction and scattering of the transmitted signal, which create constructive or destructive interference between the signal components [1]. The propagation is also affected by shadowing effects due to the presence of obstacles along the signal path.

In order to characterize the 5 GHz mobile channel for the selected environments, we calculate the path loss, Doppler power spectral density and the first order statistics per measurement scenario and then compare them for determining the influence of internal and external walls and floors on the propagation environment.

4.1 Measurement scenarios

The measurements are performed in the DLC, which represents a typical multi-floor office building of common construction materials. It has three floors and one basement, each of them with similar distributions where the hallways are vertically aligned.
We have measured different scenarios, which permits studying the signal propagation in different conditions: line-of-sight, through internal walls, through floors and through external walls.

In order to study the line-of-sight propagation, the transmitter and receiver are located in the same corridor, with line of sight between them. The corridor has large windows and has a longitude of approximately 26 m. Figure 4.1 a) shows a picture of the corridor in level 1B.

In the case of propagation through internal walls, the transmitter is located inside a lab and the receiver is moved along the same floor. The internal walls used for separating the different rooms in the building can be classified in two groups: hard partitions and soft partitions [1], as described in section 2.2.4.

The propagation through floors is studied by locating the mobile receiver one or two floors above the level where the transmitter is located. The floors of the DLC are made of metal and concrete and, therefore, the received signal is expected to have a considerable higher attenuation than in the case of walls. The distance between floors is 5 m. Figure 4.1 b) and c) show pictures of the east and central corridors in level 1, respectively, and Figure 4.1 d) shows the central corridor in level 2.

In the case of propagation through external walls, the transmitter is fixed inside the DLC and the receiver is pushed around the building. As shown in Figure 4.2 a), the exterior walls are made of metal, thick concrete and brick. Figure 4.2 b) shows the large and thick external windows that cause high attenuation of the signal for indoor to outdoor propagation.

In order to study these propagation conditions, we defined twelve measurement scenarios, which are determined by the locations of the transmitter and the receiver, according to Table 4.1:
### Table 4.1. Measurement scenarios

<table>
<thead>
<tr>
<th>Transmitter location (fixed)</th>
<th>Receiver location (mobile)</th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside the energy lab in level 1B</td>
<td>Scenario 1</td>
<td>Scenario 2</td>
<td>Scenario 3</td>
</tr>
<tr>
<td>In the hallway in level 1B</td>
<td>Scenario 4</td>
<td>Scenario 5</td>
<td>Scenario 6</td>
</tr>
<tr>
<td>In the hallway in level 2B (basement)</td>
<td>Scenario 7</td>
<td>Scenario 8</td>
<td>Scenario 9</td>
</tr>
</tbody>
</table>

**Figure 4.1.** a) East corridor in level 1B and b) level 1, c) Central corridor next to the foyer area in level 1 and d) level 2
In the cases where the transmitter is located in the basement (scenarios 7, 8, 9 and 12) and the receiver is located outside (scenarios 10, 11 and 12), the transmitting power is 30 dBm, in order to penetrate the basement ceiling and/or the external walls and windows. In the other cases, the transmitting power is 10 dBm.

Depending on the geometry of each measurement scenario, we can also consider the effect of the foyer on the propagation. This open area connects levels 1B, 1 and 2 though the stairs, as shown in Figure 4.3 a), b), c) and d), and acts as a coupling mechanism that helps to propagate the signal. Figure 4.3 d) shows that there is a metallic structure on the right part of the wall, on the ground floor of the foyer, which affects the signal propagation.
Figure 4.3. a) Side view of the foyer in level 1B, b) Stairs, c) Front view of the foyer in level 1B and d) Foyer in level 1

4.2 Channel parameters per measurement scenarios

We calculate the path loss, Doppler power spectrum and best fit PDF of the fading distribution for each measurement scenario and compare these parameters for the different propagation conditions described, which are then compared to the theoretical values. The route
followed by the receiver for each measurement scenario consists of a succession of straight
sections, which are used to calculate the distance between transmitter and receiver along the
path. The sections are indicated in different colors with the aim of studying how the channel
characteristics vary for each of these sections.

4.2.1 Transmitter located inside the lab in level 1B and receiver moving along levels 1B, 1
and 2

We are considering scenarios 1, 2 and 3, according to Table 4.1. In all these cases the
transmitter is located inside the energy lab in level 1B, in the ground floor. The receiver moves
along levels 1B, 1 and 2.

4.2.1.1 Path loss

Figure 4.4 a), Figure 4.5 a) and Figure 4.6 a) show the path of the receiver in levels 1B
(scenario 1), 1 (scenario 2), and 2 (scenario 3), respectively. The colored arrows describe the
moving direction of the receiver per straight section. According to this, scenario 1 describes the
propagation through walls, while scenarios 2 and 3 add the propagation through floors and the
effect of the foyer area on the received signal.

Figure 4.4 b), Figure 4.5 b) and Figure 4.6 b) show the path loss per section for each
scenario, which are compared to the free space path loss. The gray color represents the
instantaneous path loss and the colored lines indicate the averaged path loss per straight section
calculated based on Lee’s method [27].

In the case of scenario 1, as shown in Figure 4.4 b), we compare the path loss and free
space path loss for sections 1 and 9, from which it is inferred that the attenuation caused by the
wall and obstacles between the transmitter location and the east corridor in level 1B is approximately 10 dB. This value agrees to the interior office wall transmission loss estimated by Chung and Bertoni in 5.2 GHz [22], which was found to be between 5 to 10 dB. Additionally, it is noted that the signal is attenuated approximately between 5 dB to 10 dB more when the receiver is moving on the right part of the atrium, which corresponds to sections 2, 6, 7 and 9, due to the metallic structure on the wall of the foyer, showed in Figure 4.3 d), in the direction of the signal path.

Figure 4.5 b) indicates that the path loss for scenario 2 increases with the distance. The signal received in level 1 is propagated mainly through the floor and, as expected, the path loss decreases with the distance.

Figure 4.6 b) shows the path loss plot for scenario 3. Since the receiver is now on level 2, the effect of the propagation through the foyer will be dominant in the sections near this open space. This is the reason why the path loss decreases with the distance near the end of the east and west corridors and in the central corridor next to the foyer.

Figure 4.7 shows the average path loss for each scenario based on calculations using Lee’s method, as well as the linear least-squares regression fit and slope (‘n’) for each. From the plots, we can infer that the attenuation for each floor is approximately 20 dB, which is similar to the one measured by Rappaport [10], who considered values between 20 and 30 dB for frequencies of 1300 MHz.

The slope values are approximately the same for scenarios 1 (‘n’=4.48) and 2 (‘n’=4.34) and are according to the range of ‘n’ expected for NLOS in building propagation in this band. According to the measurements performed by Cheung and Prettie in a residential environment [33], the NLOS path loss exponents are ‘n’=4.7 for UNII-I, ‘n’=4.48 for UNII-II and ‘n’=4.59
for UNII-III [33], which are similar to the ones found for the 5.41 GHz frequency used in this work. This slope is also similar to the one calculated by Kivinen et al. [21], who measured this parameter in office and commercial buildings at 5.3 GHz and found that it has values between 2.9 and 4.8 in NLOS conditions, depending on the material of the partitions and walls along the path. These values are also in concordance with the more general slopes provided by Rappaport for obstructed in-building, where ‘n’ ranges from 4 to 6 [1].

In the case of scenario 3, we divide the path loss graph in two sections. The first one has a positive slope of 5.08, which corresponds to the propagation through floors, from level 1B to level 2. The second section of the path loss plot for this scenario has a negative slope of -3.88, which indicates that the path loss decreases with the distance. The reason is because, at a relatively far distance from the transmitter and according to the distribution of the building, the signal propagated through the foyer is stronger than the one transmitted through floors and, the closer the receiver is from the foyer, the stronger the signal.

4.2.1.2 Doppler power spectral density and first order statistics

The Doppler frequency shift is caused by the relative movement between transmitter and receiver and due to the scattering environment. The VSA permits calculating the positive and negative Doppler frequency shift components in order to determine if the receiver is moving towards or away from the transmitter and study the mobile propagation channel.

Figure 4.8 a), Figure 4.9 a) and Figure 4.10 a) present the power spectral density vs. time plots for scenarios 1, 2 and 3. The straight sections along the path are separated by vertical black lines.
The maximum Doppler frequency shift is calculated using the formula given in Equation 4.1.

\[ \Delta f = \frac{v \times f}{c} \]  \hspace{1cm} 4.1

Considering the constant walking velocity at which the receiver is moved, \( v = 3 \text{ km/h} \), \( f = 5.41 \text{ GHz} \) and \( c = 3 \times 10^8 \text{ m/s} \), the maximum Doppler frequency shift (\( \Delta f \)) is 15 Hz, which corroborates what is shown in the plots.

Line-of-sight conditions in outdoor environments are characterized by a significantly dominant signal component, which indicates that the signal is coming from one specific direction. In contrast, in an indoor environment, the signal is more scattered and different frequency components arrive at the receiver. Depending on the indoor environment, a strongest frequency component can arrive at the receiver, which indicates that the signal is coming from mainly one direction and the small-scale fading envelope will better fit a Rician distribution [1][3].

For example, sections 1 and 9 in scenario 1, shown in Figure 4.8 a), present a main frequency shift component which corresponds to intervals when the receiver is moving away and towards the transmitter, respectively. The strongest \( \Delta f \) along section 1 is approximately -15 Hz and, for section 9, is 15 Hz.

Sections 1, 4, 5 and 8 of scenario 2, shown in Figure 4.9 a), correspond to the sections where the receiver is moved along level 1. The intense yellow color indicates the presence of a strong frequency shift component, which is approximately -15 Hz along sections 1 and 5 (moving away from the transmitter) and 15 Hz for sections 4 and 8 (moving towards the transmitter). In all these cases, it is also shown a reflection of a main signal component, which
has the same frequency shift, but less magnitude and opposite sign, due to the reflection on walls, ceiling and floor.

On the other hand, in a rich scattering environment, there will not be any strong frequency component and the PDF of the signal envelope will better fit a Rayleigh distribution \([1][3]\). For example, the signal is very scattered in sections 2 and 3 of scenario 1, as shown in Figure 4.8 a), which corresponds to the sections when the receiver has passed the corridor, turned down the corner and got into the foyer area. In this case, the components of the received signal are coming from many directions and the small-scale fading has a Rayleigh distribution. The same happens for sections 2, 3, 6 and 7 of scenario 2, as shown in Figure 4.9 a), which corresponds to the sections when the receiver is moving in the foyer area in level 1.

Sections 1 and 9 in scenario 1, showed in Figure 4.8 b), have several time intervals when k-factor>0.5, which indicate the presence of a stronger LOS component. Similarly, as shown in Figure 4.9 b), sections 1, 4, 5 and 8 in scenario 2 indicate the presence of a stronger LOS component because the receiver is moved along the corridors and the signal is mainly propagated through floors and not through the foyer. Sections 2, 3, 6 and 7 in the same scenario correspond to the intervals when the receiver is moved near foyer area. It is noted that the received signal has more scattered frequency components and, therefore, the k-factor is lower than in the other cases.

In the case of scenario 3, shown in Figure 4.10 a), sections 1, 2 and 9 indicate that the received signal is more scattered than in the previous two scenarios. They present a weaker main frequency component, since the received signal is mainly propagated through floors. These sections correspond to the east corridor in level 2 and it is noted that \(\Delta f <0\) when the receiver moves away from the transmitter and \(\Delta f >0\) when it moves towards it. Sections 3, 4, 7, and 8
correspond to central corridor next to the foyer area, which contributes to the propagation of the signal. The path loss is reduced in these sections, as seen in Figure 4.6 b), but since the signal components arrive from different directions, the received signal gets more scattered and, therefore, the k-factor decreases, as shown in Figure 4.10 b). Section 5 corresponds to the section when the receiver in level 2 is moving in the west corridor towards the transmitter. As expected, it is noted that there is a strong positive frequency component, which might also be due to a leakage signal propagated through the doors of the elevator, located right next to this corridor. Coupling through the waveguide structure of the elevator shaft can propagate the signal from level 1B to level 2, which makes the Doppler spectrums different for the west and east corridors, despite the approximate symmetry of the locations of both corridors with respect to the transmitter. There is also another negative component, which is stronger near the foyer, which can be caused by the movement of the receiver away from this area.

Additionally, we are plotting the power spectral density and best fit PDF of the fading distribution for selected time intervals in order to analyze how the signal changes along the path. Figure 4.11 a) and Figure 4.12 a) show the power spectral density (PSD) of the received signal using the Welch method, which is compared to the raw periodogram.

Figure 4.11 a) shows the PSD calculated for a time window of 3 seconds in section 1 of scenario1. During this time, the channel is considered to be stationary. We observe that the peak frequency shift is approximately $\Delta f = -15$ Hz, because of the strong line of sight component along this section. For the time interval from 16 to 19 seconds, the Rician k-factor is 1.7 and, since it is greater than 0.5, the envelope distribution can be classified as Rician. The histogram of the signal and its best fit PDF plots are shown in Figure 4.11 b). As expected, the Rician PDF fits better the histogram than the Rayleigh PDF. The latter can be confirmed by calculating the goodness of fit,
a method that indicates how successful the data fits the statistical model. In order to measure the goodness of fit, we use the R-squared ($R^2$) method, also called coefficient of determination, which calculates the square of the correlation coefficient between two vectors. It can take values between 0 and 1, where 1 indicates a perfect fit. For the Rician distribution fit, $R^2$ is 0.88 and, for the Rayleigh fit, $R^2$ is 0.83, which corroborates that the first one is the best fit PDF of the fading distribution.

Similarly, we analyze the time interval from 46 to 49 seconds in scenario 2, which corresponds to section 2, when the receiver moves along the foyer area in level 1. The power spectral density, shown in Figure 4.12 a) indicates that there is not a dominant frequency component in this interval. Figure 4.12 b) shows that both, Rayleigh and Rician PDFs fits, are almost the same and both fit the histogram of the signal envelope very well, since Rayleigh distribution can be theoretically considered as a Rician distribution with $k$-factor=0 [1][8]. From the data, the calculated $k$-factor is 0.0034, which is less than the empirical 0.5 threshold that we set for Rayleigh fading in these measurements. The value of $R^2$ for the Rayleigh fit is 0.8073 and, for Rician fit, $R^2$ is 0.8072. The similarity of both values is because the Rayleigh distribution is a special case of Rician distribution and, therefore, it means that Rayleigh is the best distribution fit for this interval.
Figure 4.4. Scenario 1: Transmitter located inside the lab in level 1B and receiver moving along level 1B. a) Route and b) Path loss per section
Figure 4.5. Scenario 2: Transmitter located inside the lab in level 1B and receiver moving along level 1. a) Route and b) Path loss per section
Figure 4.6. Scenario 3: Transmitter located inside the lab in level 1B and receiver moving along level 2. a) Route and b) Path loss per section
Figure 4.7. Path loss and path loss slope for scenarios 1, 2 and 3
Figure 4.8. Scenario 1: Transmitter located inside the lab in level 1B and receiver moving along level 1B. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.9. Scenario 2: Transmitter located inside the lab in level 1B and receiver moving along level 1. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.10. Scenario 3: Transmitter located inside the lab in level 1B and receiver moving along level 2. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.11. Rician fading in section 1 of scenario 1: a) power spectral density and b) distribution fitting plot
Figure 4.12. Rayleigh fading in section 2 of scenario 2: a) power spectral density and b) distribution fitting plot.
4.2.2 Transmitter placed in the hallway in level 1B and receiver moving along levels 1B, 1 and 2

We are considering scenarios 4, 5 and 6, according to Table 4.1. In all these cases the transmitter is located in the hallway in level 1B and the receiver moves along levels 1B, 1 and 2.

4.2.2.1 Path loss

Figure 4.13 a) and Figure 4.14 a) show the path of the receiver in levels 1B (scenario 4), 1 (scenario 5), and 2 (scenario 6), respectively. Figure 4.13 b) and Figure 4.14 b) and Figure 4.15 b) show the path loss per section for each scenario compared to the free space path loss.

Propagation in scenario 4 can be divided in two parts: propagation with line of sight (transmitter and receiver located in the same hallway) and without line of sight (when the receiver is being moved in the foyer area). As show in Figure 4.13 b), the LOS section corresponds to distances between transmitter and receiver less than 11 meters, and is characterized by the presence of a waveguide effect [1]. Because of its geometry, the hallway acts as a waveguide that causes the signal to propagate through continuous reflections on walls, ceiling and floor. This effect contributes to the propagation of the signal and causes path loss values lower than the free space path loss.

The NLOS section corresponds to distances greater than 11 meters, which is determined by the point where the receiver turns down the corner and moves into the foyer area. The waveguide effect is not present and the path loss is higher than the free space path loss. The second part of section 4 and the whole section 5 present higher path losses than in sections 6 and 7. The reason is because the signal is propagated through walls in the direction of the first two
sections, while in the other two cases, it is propagated through the corridor, which causes reduced path losses.

Additionally, in indoor propagation, the near and far-field effects of the antenna are irrelevant, because the environment scatters the signal. We see in Figure 4.13 b) that the average path loss is higher than the free space path loss for distances less than approximately 3 meters and is lower for larger distances, in which the waveguide effect is present.

In the case of scenario 5, when the receiver is moving in level 1, the path loss increases with the distance for the sections right above the corridor where the transmitter is located, as shown in Figure 4.14 a). In these sections, since the hallways are aligned, the signal is propagated due to a strong coupling through the floor. For sections 4 and 9 the slope of the path loss remains approximately the same than in the previous case, since the extra path loss due to the walls penetration is compensated by the contribution of the foyer area on the propagation. Sections 5 and 8 experience approximately between 5 and 15 dB less path loss than sections 6 and 7 because of their proximity to the foyer area, which contributes to the signal propagation.

As seen in Figure 4.15 a), the path loss curves for scenario 6 are similar to the ones in scenario 5, except that the signal received near the foyer, which corresponds to sections 4 and 9 and the areas of sections 5 and 8 close to the foyer area, was propagated mainly through this open area and, in a much lower degree, through floors.

Figure 4.16 shows a comparison of the path loss for each scenario and their slope (‘n’). We infer that the signal attenuation from level 1 to level 2 is approximately 20 dB, which is according to the value estimated in section 4.2.1.1. In the case of scenario 4, the path loss has a dual slope and the breakpoint is determined by the distance at which the receiver leaves the corridor (LOS section) and gets into the foyer (NLOS section) [34][23][35]. The slope for the
LOS section is 1.22, which is low due to the presence of a waveguide effect, since ‘n’ < 2 [1], and also because the far-field effect of the antenna does not practically apply to indoor propagation. This ‘n’ value is similar to the one obtained in the measurements performed by Xu et. al and Kivinen et al. at 5.2 GHz and 5.3 GHz, respectively, for office or commercial buildings in indoor conditions [21][23]. They estimated path loss slopes between 1.3 and 1.5 when the transmitter and receiver were located in the same room or corridor with line-of-sight between them, which evidenced a waveguide effect. Additionally, in our measurements the path loss slope in level 1B is lower than the ones for the LOS sections of scenarios 5 (‘n’=1.65) and 6 (‘n’=1.57), but they are less than ‘n’=2. This indicates that there is still a waveguide effect in each of them, caused by the signal coupling through floors due to the vertically aligned distribution of the corridors. The signal propagates through multiple reflections on these corridors, causing a waveguide effect.

The slope for the NLOS section of scenario 4 is 4.56, which is according to the expected values for obstructed in-building propagation in this frequency [36] and is similar to the slope of 4.48 obtained for scenario 1, in section 4.2.1.1. In the case of the NLOS sections of scenarios 5 and 6, the slopes are -1.83 and -6.35, respectively, since the coupling mechanism caused by the foyer area contributes to the propagation of the signal. This effect is more significant in higher floors, which causes the path loss to have a more negative slope in level 2.

4.2.2.2 Doppler power spectral density and first order statistics

Figure 4.17 a), Figure 4.18 a) and Figure 4.19 a) present the power spectral density vs. time plots and Figure 4.17 b), Figure 4.18 b) and Figure 4.19 b) show the k-factor vs. time plots for scenarios 4, 5 and 6.
Sections 1, 2, 10 and 11 in scenario 4, shown in Figure 4.17 a), present a main frequency shift component which corresponds to intervals when the receiver is in line of sight with the transmitter and is moved along the hallway. The power spectral density concentrates around a single dominant frequency shift component, which is more noticeable than in the case of propagation through walls studied in scenario 1. The strongest \( \Delta f \) along sections 1 and 10 is approximately 15 Hz and, for sections 2 and 11, is -15 Hz. For the other sections, the signal is scattered and there is no dominant frequency shift component. This is reflected in Figure 4.17 b), which shows much higher Rician k-factors for sections 1, 2, 10 and 11 (up to 9), while the values of this parameter remain low (less than 3) for the NLOS sections, similar to the values obtained for scenario 1, as expected.

In the case of scenario 5, the signal components are more scattered, as shown in Figure 4.18 a), due to the transmission through the floor. Sections 1, 2, 11 and 12 present a slightly stronger frequency shift component which corresponds to the intervals when the receiver moves along the hallway. The frequencies are positive for sections 1 and 10, when the receiver is moving towards the transmitter, and negative for sections 2 and 11, when it is moving away from the transmitter. Sections 5 and 6 show a slightly stronger negative frequency component, which indicate that the signal is mainly coming from the foyer area and the receiver is moving away from the foyer, in the west corridor. Sections 7 and 8 represent the opposite, when the receiver is moved towards the foyer, which generates a positive frequency shift component. Figure 4.18 b) shows that the signal is less scattered in sections 5 and 8, which represent the portion of the east corridor near the foyer. The Rician k-factor increases for these two sections and takes values up to 3.5, while for the other ones, it remains between 0 and 1.5. It is also noticed that, despite the signal has less path loss when the receiver is in the foyer, the signal is also more scattered.
because it has been propagated through this open area, which acts as an open cavity that scatters the signal.

In the case for scenario 6, as shown in Figure 4.19 a), the signal received in the east corridor is very scattered due to the weak propagation through floors and from the foyer. The propagation leakage effect from the foyer is much more significant in the west corridor, in sections 5, 6, 7 and 8, because there is a glass wall that divides the central corridor and the foyer and goes up to the west corridor, as shown in Figure 4.1 d). The signal received through the foyer penetrates this wall, gets into the central corridor and then is propagated through the west corridor, which acts as a waveguide. This is the reason why, even when the received signal power is lower because of the larger distance from the transmitter, especially in sections 6 and 7, the signal is more scattered and the k-factor is higher in the west corridor. According to Figure 4.19 b), the k-factor is higher for sections 5, 6, 7 and 8, reaching its maximum values around k=6, while, for the other scenarios, this parameter remains between 0 and 1, which indicates a richer scattering environment. Sections 5 and 6 mainly have a negative frequency shift component, which means that the received signal is coming from the foyer and the receiver is moving away from it. Sections 7 and 8 have a stronger positive frequency shift component, which indicates that the receiver is moving towards the foyer. The window glass is not present in the east corridor and, therefore, the signal gets more scattered.
Figure 4.13. Scenario 4: Transmitter located in hallway in level 1B and receiver moving along level 1B. a) Route and b) Path loss per section
Figure 4.14. Scenario 5: Transmitter located in hallway in level 1B and receiver moving along level 1. a) Route and b) Path loss per section
Figure 4.15. Scenario 6: Transmitter located in hallway in level 1B and receiver moving along level 2. a) Route and b) Path loss per section
Figure 4.16. Path loss and path loss slope for scenarios 4, 5 and 6
Figure 4.17. Scenario 4: Transmitter located in hallway in level 1B and receiver moving along level 1B. a) Power spectrum vs. time and b) K-factor vs. time.
Figure 4.18. Scenario 5: Transmitter located in hallway in level 1B and receiver moving along level 1. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.19. Scenario 6: Transmitter located in hallway in level 1B and receiver moving along level 2. a) Power spectrum vs. time and b) K-factor vs. time
4.2.3 Transmitter placed in the basement (level 2B) and receiver moving along levels 1B, 1 and 2

The transmitter is located in the hallway in level 2B and the receiver moves along levels 1B, 1 and 2, which correspond to scenarios 7, 8 and 9, respectively, according to Table 4.1.

4.2.3.1 Path loss

Figure 4.20 a), Figure 4.21 a) and Figure 4.22 a) show the path of the receiver in levels 1B (scenario 7), 1 (scenario 8), and 2 (scenario 9), respectively. Figure 4.20 b), Figure 4.21 b) and Figure 4.22 b) show the path loss per section for each scenario compared to the free space path loss.

The path in scenario 7 can be divided into two parts, depending if the receiver is located in the hallway right above the transmitter or in the foyer area. For both parts, the path loss includes the attenuation of the signal transmitted from the basement in level 2B to level 1B. According to the geometry, the second part corresponds to distances larger than 21 meters, where the path loss increases considerably because the signal is also attenuated by walls, as shown in Figure 4.20 b). When the receiver is moved along sections 4 and 5, the signal is attenuated up to 10 dB more than in sections 6 and 7, despite the fact that the distances are approximately the same for both pairs of sections. This is because the received signal is propagated mainly through the corridor instead of the through the walls, similar to what occurred in scenario 4.

In the case of scenario 8, when the receiver is moving on level 1, the path loss increases with the distance for the sections right above the corridor where the transmitter is located, as shown in Figure 4.21 b). For sections 3, 4, 9 and 10, along the central corridor next to the foyer, the signal is slightly more attenuated because it also has to penetrate the wall when the receiver
goes around the corner. The attenuation is not too high due to the signal components that propagate through the foyer area from level 1B to level 1. Sections 5, 6, 7 and 8 experience more path loss, since they are more affected by the presence of walls along the signal path for each section.

As shown in Figure 4.22 b), the path loss in scenario 9 follows similar characteristics than in scenario 8, but the signal received near the foyer is more attenuated because of the wall penetration loss, which is much higher than the signal contribution from the foyer. In contrast, in the case of scenario 6, the contribution of the foyer is higher since the transmitter is in level 1B, which is connected to level 2 through the foyer. In the case of scenario 9, the transmitter is located in the basement on level 2B, which is all covered by concrete. The path loss for sections 5, 6, 7 and 8, along the west corridor, are even more attenuated because the little effect of the foyer significantly decreases as we increase the distance of the receiver from this open area.

Figure 4.23 shows a comparison of the path loss for each scenario and their slopes. We confirm that the attenuation per floor is approximately 20 dB, which is the same value obtained in sections 4.2.1.1 and 4.2.2.1 and is similar to the values estimated in previous measurements [36].

In the case of scenario 7, the path loss slope in the corridor is 1.86, which indicates that there is still a waveguide effect since ‘n’ < 2, due to coupling effects from the transmitter located in the hallway right below where the receiver is moved. Because of the attenuation though the walls, the slope in the NLOS section is 4.14, which is similar to the slopes obtained in scenarios 1, 2, 3 and 4 for NLOS conditions, as discussed in sections 4.2.1.1 and 4.2.2.1.

In the case of scenario 8, ‘n’=2.45 along the corridor, which is higher than the slope obtained for the LOS section in the previous scenario, due to the propagation through the foyer.
from level 1B to level 1. In the NLOS sections of scenario 8, \( n = 2.59 \), which is lower than in scenario 7 because the propagation through the foyer decreases the path loss considering the specific geometry of the building.

In the case of scenario 9, \( n = 0.25 \) in the corridor, which is much lower than in the previous scenarios because of the coupling mechanism due to the leakage from the foyer area. In this case, the signal is mainly propagated though the foyer instead of through floors. In the NLOS sections of the same scenario, \( n = -0.54 \), which is also due to the propagation through the open area.

**4.2.3.2 Doppler power spectral density and first order statistics**

Figure 4.24 a), Figure 4.25 a) and Figure 4.26 a) present the power spectral density vs. time plots and Figure 4.24 b), Figure 4.25 b) and Figure 4.26 b) show the k-factor vs. time plots for scenarios 7, 8 and 9.

Sections 1, 2, 10 and 11 in scenario 7, as shown in Figure 4.24 a), present a main frequency shift component which corresponds to intervals when the receiver is moving in the corridor above the transmitter. The strongest Doppler shifts along sections 1 and 10 are approximately 15 Hz and, for sections 2 and 11, are approximately -15 Hz. For the other sections, the signal looks more scattered because of the propagation through walls, which adds to the effect of signal penetration from the basement. This can be observed in Figure 4.24 b), which shows higher Rician k-factors for sections 2 and 10 (up to 3). The values of the k-factor are lower for the other sections.

In the case of scenario 8, the signal components are much more scattered, as shown in Figure 4.25 a), due to the transmission through one additional floor. Sections 1, 2, 11 and 12
present slightly stronger frequency shift components, which corresponds to the intervals when the receiver moves along the hallway. The Doppler shifts are positive for sections 1 and 11, when the receiver is moving towards the transmitter, and negative for sections 2 and 12, when it moves away from the transmitter. The other sections are more scattered and the k-factors are less than 1.5, as noted in Figure 4.25 b).

In the case for scenario 9, as shown in Figure 4.26 a), sections 1, 2, 11 and 12 also present slightly stronger frequency components because of the relative movement of the receiver with respect of the transmitter, located three levels below. There is also propagation leakage from the foyer, which is much more significant in sections 5, 6, 7 and 8, located in the west corridor. Sections 5 and 6 have mainly a negative Doppler shift component, which means that the received signal is mainly coming from the foyer and the receiver is moving away from it. Sections 7 and 8 have a stronger positive frequency shift component, which indicates that the receiver is moving towards the foyer. Figure 4.26 b) corroborates these observations by showing that the k-factor is slightly higher for sections 5, 6, 7 and 8, reaching maximum values around k=1.8.
Figure 4.20. Scenario 7: Transmitter located in level 2B and receiver moving along level 1B. a) Route and b) Path loss per section
Figure 4.21. Scenario 8: Transmitter located in level 2B and receiver moving along level 1. a) Route and b) Path loss per section
Figure 4.22. Scenario 9: Transmitter located in level 2B and receiver moving along level 2. a) Route and b) Path loss per section
Figure 4.23. Path loss and path loss slope for scenarios 7, 8 and 9
Figure 4.24. Scenario 7: Transmitter located in level 2B and receiver moving along level 1B. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.25. Scenario 8: Transmitter located in level 2B and receiver moving along level 1. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.26. Scenario 9: Transmitter located in level 2B and receiver moving along level 2. a) Power spectrum vs. time and b) K-factor vs. time
4.2.4 Transmitter placed in the hallway or inside the lab in level 1B or in the hallway in level 2B and receiver located outside, moving around the DLC.

The receiver moves around the DLC, in a U-shaped trajectory. The transmitter is located in each one of the three different places described in the previous scenarios: in the energy lab in level 1B, in the hallway in level 1B or in the hallway in level 2B, which correspond to scenarios 10, 11 and 12, respectively, according to Table 4.1.

4.2.4.1 Path loss

Figure 4.27 a), Figure 4.28 a) and Figure 4.29 a) show the route of the receiver when the transmitter is located in the hallway in level 1B (scenario 10), in the lab in level 1B (scenario 11) and in the hallway in level 2B (scenario 12), respectively. The path loss in each of these scenarios is determined by the number and characteristics of interior and exterior walls and windows, as well as other obstacles in the direct path between transmitter and receiver. Figure 4.27 b), Figure 4.28 b) and Figure 4.29 b) show the path loss per section for each scenario compared to the free space path loss.

In the case of scenario 10, as shown in Figure 4.27 b), section 1 has higher attenuation due to the blockage effect caused by a metallic structure along the signal path, near the receiver. The path loss for the same distance is lower for section 3 than for section 2, because there are fewer interior walls along the signal path and also because the foyer acts as a cavity that contributes the propagation of the signal in the first case. The path loss is slightly lower in section 4 compared to section 3 because the signal travels mainly through the corridor inside the building and then is transmitted through the external walls and windows. In the case of section 3, it needs to go through some interior walls, which increases the signal loss. Section 5 experiences
more attenuation near the southeast corner because of the additional number of rooms along the direct signal path. Section 6 has the lowest attenuation because there is only one exterior window between the transmitter and the receiver over most of its path.

In the case of scenario 11, shown in Figure 4.28 b), the attenuations for sections 1 and 4 are similar because the number of interior and exterior walls and obstacles are approximately the same for each direction. Section 3 has slightly higher attenuation than section 2 because of the metallic structure on the wall of the foyer in that direction, shown in Figure 4.3 c). In the case of section 5, the furthest part of it has more attenuation due to the blockage effect due to the concrete structures along the direct path, including the stairs.

As shown in Figure 4.29 b), sections 1 and 2 of scenario 12 have similar attenuations due to the location of the transmitter and the propagation environment. As in scenario 10, the furthest part of section 2 has lower attenuation because the signal is propagated through the corridor and then penetrates the exterior walls and windows. Because of this reason, the attenuation is also lower for section 3, compared to section 4. The loss increases for section 5, due to the higher number of interior walls and obstacles in the trajectory of the signal.

Figure 4.30 shows a comparison of the path loss for each scenario and their slopes. We corroborate that the attenuation per floor is approximately 20 dB, according to the value estimated in previous scenarios. The path loss slopes for scenarios 10, 11 and 12 are 4.62, 3.64 and 5.08, respectively. These values are close to the ones obtained in previous NLOS indoor measurements, which consider slopes between 4.4 and 4.7 [33]. The path loss in these three scenarios includes the effects of interior and exterior walls and windows, as well as obstacles along the transmission path of the signal. Scenario 10 has a path loss 5 to 10 dB higher than scenario 11, because of the extra interior partition that the signal has to penetrate.
4.2.4.2 Doppler power spectral density and first order statistics

Figure 4.31 a), Figure 4.32 a) and Figure 4.33 a) present the power spectral density vs. time plots and Figure 4.31 b), Figure 4.32 b) and Figure 4.33 b) show the k-factor vs. time plots for scenarios 10, 11 and 12.

According to Figure 4.31 a), section 1 in scenario 10 does not have a main frequency component since the signal is scattered due to a blockage effect caused by a metallic obstacle along the direct path. Section 2 shows a slightly stronger positive frequency component, despite the receiver is moving away from the transmitter. The reason is because the signal is coming mainly from the front part of the building and, in a much lower degree from the direct straight path between the transmitter and receiver. Sections 3 and 4 correspond to the path where the receiver moves in front of the main entrance. The signal received in these sections is more scattered due to the presence of internal walls and the foyer in the transmission path. The foyer acts as a cavity that contributes to propagate the signal, but also scatters its components in different directions. Section 3 has a stronger positive Doppler frequency shift, since the receiver moves towards the transmitter, while section 4 has primarily a negative Doppler frequency component as it moves away from the transmitter. Sections 5 and 6 suffer less scattering than the other sections, because the signal is basically coming from the direct path from the transmitter. In the case of section 5, where the receiver moves towards the transmitter, the Doppler frequencies are mainly positive, while for section 6, they are mainly negative as they move away from the transmitter. In average, as shown in Figure 4.31 b), sections 2, 5 and 6 have higher Rician k-factors than the other sections, since the signal components arrive at the receiver from mainly one direction.
As shown in Figure 4.32 a) section 1 of scenario 11 has a considerably stronger negative Doppler frequency component, since the receiver is moving in the west section outside the DLC, in a direction away from the transmitter. This is also shown in Figure 4.32 b), where it is noted that the Rician k-factor is much higher than in any other scenarios previously studied and reaches values of up to 11, because part of the signal is propagated outdoors, which causes less reflections in the environment. In the case of sections 2 and 3, the signal becomes highly scattered because of the influence of the internal walls and foyer in the path. This is the reason why the values of the k-factor are much lower than in other sections. Sections 4 and 5 show a clear dominant Doppler frequency shift component, which is positive for section 4 and negative for section 5, as the receiver moves towards and away from the transmitter, respectively. The k-factor for section 4 is as high as in section 1 for the same reason and its maximum value is 11. The k-factor is much lower in section 5, because of the blockage effect caused by the concrete structures of the building.

In the case of scenario 12, sections 1 and 2 represent the east part of the path around the DLC, closer to the transmitter, which is located in the basement, in level 2B. As shown in Figure 4.33 a), the Doppler frequency component for section 1 is positive since the receiver is moving towards the transmitter. In the case of section 2, where it moves away from the transmitter, the main Doppler frequency shift component is negative. For both sections, as shown in Figure 4.33 b), the highest maximum value of the k-factor is around 3, which is lower than in the two previous scenarios because the signal is more scattered due to its propagation from the basement. Sections 3 and 4, which correspond to the area in front of the main entrance of the DLC, show positive and negative Doppler frequencies, respectively, as the receiver is moving towards and away from the transmitter. In the second half of section 4, the signal becomes more scattered
because of the additional number of walls the signal travels through. This is also shown in the k-factor values, which are less than 1. Section 5 is even more scattered, since it corresponds to the east part of the DLC, the furthest from the transmitter. Although there is a slightly stronger positive Doppler frequency component as the receiver moves towards the transmitter, the signal components are actually heavily scattered due to the multipath effect caused by the transmission of the signal from the basement and consecutive reflections that cause the k-factor to have values less than 1.
Figure 4.27. Scenario 10: Transmitter located in hallway in level 1B and receiver moving around the DLC. a) Route and b) Path loss per section
Figure 4.28. Scenario 11: Transmitter located in lab in level 1B and receiver moving around the DLC. a) Route and b) Path loss per section
Figure 4.29. Scenario 12: Transmitter located in level 2B and receiver moving around the DLC. 
   a) Route and b) Path loss per section
**Figure 4.30.** Path loss and path loss slope for scenarios 10, 11 and 12
Figure 4.31. Scenario 10: Transmitter located in hallway in level 1B and receiver moving around the DLC. a) Power spectrum vs. time and b) K-factor vs. time.
Figure 4.32. Scenario 11: Transmitter located in lab in level 1B and receiver moving around the DLC. a) Power spectrum vs. time and b) K-factor vs. time
Figure 4.33. Scenario 12: Transmitter located in level 2B and receiver moving around the DLC. 
  a) Power spectrum vs. time and b) K-factor vs. time
4.3 Comparative path loss plots for different propagation conditions

We generate plots that permit comparing the values of the path loss curves for different scenarios and determining the attenuation through internal and external walls and floors. These plots are generated according to the scenarios described in the previous sections, for different propagation conditions.

4.3.1 Transmitter placed inside the lab or hallway in level 1B and receiver moving along level 1B and outside the DLC

We compare the path loss slopes for scenarios 1, 4, 10 and 11 in order to determine graphically the attenuation of the signal through interior and exterior walls and floors. Figure 4.34 shows that the slope for the LOS part of scenario 4 (transmitter located in hallway in level 1B and receiver moving in the same level) is 1.22, which indicates the presence of a waveguide effect, since ‘n’<2. The slope for the NLOS section is 4.56, which is similar to the one for scenario 1 (transmitter located in lab in level 1B and receiver moving in the same level), where ‘n’=4.59. Both values consider the attenuation through the walls, but the difference on the values of path loss is due to the number of walls along each path from the transmitter. This difference is between 5 and 10 dB, which is the average attenuation per interior wall, according also to the value calculated in scenario 1. The slopes obtained for scenarios 10 and 11, in which the receiver moves outside the DLC and the transmitter is located in the hallway or in the lab in level 1B are 3.64 and 4.62, respectively. These values are approximately similar to the one slopes obtained for other scenarios in this plot. Comparing the slopes for scenarios 1 and 10, the in-building attenuation is approximately 25 dB.
4.3.2 Transmitter placed inside the lab in level 1B and receiver moving along level 1 or transmitter placed in the basement in level 2B and receiver moving along level 1B

Figure 4.35 compares the path loss slopes for scenarios 5 (transmitter located in the hallway in level 1B and receiver moving along level 1) and 7 (transmitter located in the hallway in level 2B and receiver moving along level 1B). In both cases, the transmitter is fixed in the middle of the hallway and the receiver is located one level above.

The comparative plot permits confirming that the floor penetration from level 2B to 1B is the same than the one from level 1B to level 1. The LOS parts of both measurements have approximately similar path losses and path loss slopes.
The NLOS parts for both of them are different because of the structure of the building and the geometry of the paths. The signal propagated from level 2B to level 1B is transmitted almost only through floors, since there are not open areas between them. There might be some leakage from the elevator, but the effect is negligible in the measurements since it is far from the path of the receiver. In the case of the reception in level 1, the coupling mechanism through the foyer contributes to the propagation of the signal, which decreases the path loss as the receiver gets closer to this area. This is the reason why ‘n’=4.14 for scenario 10 and ‘n’=-1.83 for scenario 11.

![Figure 4.35. Path loss and path loss slope for scenarios 9 and 12](image-url-1)

Figure 4.35. Path loss and path loss slope for scenarios 9 and 12
4.4 Empirical path loss model for the DLC

According to the measurements performed, we model the propagation in the DLC to the attenuation factor model [11] and compare the results with the 802.11ax channel model [15].

4.4.1 Summary of the path loss parameters measured in the DLC

Table 4.2 and Table 4.3 summarize the values of path loss parameters obtained from the measurements performed in the DLC.

As shown in Table 4.2, the path loss slope for in-building line-of-sight on the same floor is around 1.2 and, if transmitter and receiver are in different floors, the slope is 1.7. These values are consistent with the ones obtained by Xu et. al [23] and Kivinen et al. at [21] for measurements in 5.2 GHz in office buildings and 5.3 GHz in commercial buildings, respectively. In case of obstructed in-building conditions, the path loss slope measured is approximately 4.5, which agrees to the value obtained by Cheung and Prettie for the U-NII bands in residential environments [33].

Table 4.2. Typical path loss slopes for different environments in the DLC

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path loss slope (‘n’)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-building line-of-sight (same floor)</td>
<td>1.2</td>
</tr>
<tr>
<td>In-building line-of-sight (different floors)</td>
<td>1.7</td>
</tr>
<tr>
<td>Obstructed in-building</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 4.3 shows the structure losses measured in the DLC. In the case of internal walls, we found that the loss is between 5 to 10 dB, which agrees to the value estimated by Chung and
Bertoni in 5.2 GHz in an office environment [22]. The loss per floor is approximately 20 dB, which is similar to the value measured by Rappaport [10] in 1300 MHz. The in-building penetration measured in the DLC is 25 dB.

**Table 4.3.** Estimated structure losses in the DLC

<table>
<thead>
<tr>
<th>Structure</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal walls</td>
<td>5-10</td>
</tr>
<tr>
<td>Floors</td>
<td>20</td>
</tr>
<tr>
<td>External walls and windows</td>
<td>25</td>
</tr>
</tbody>
</table>

4.4.2 Attenuation factor model

As indicated in section 2.2.4.4, the attenuation factor model is described by Equation 4.2 [11]:

$$\bar{PL}(d)[dB] = \bar{PL}(d_0)[dB] + 10n_{sf} \log \left( \frac{d}{d_0} \right) + FAF[dB] + \sum PAF[dB] \quad \text{Equation 4.2}$$

The parameter $n_{sf}$ indicates the path loss slope (‘n’) in the same floor determined by applying a regression fit to the measured path loss values, which are indicated in Table 4.2. FAF (Floor Attenuation Factor) indicates the floor attenuation factor for a specified number of building floors and PAF (Partition Attenuation Factor) indicates the attenuation factor for a specific number of walls or partitions along the propagation path [1]. The values of these parameters obtained from the measurements are indicated in Table 4.3. Since the path loss values obtained approximate to this model, we can empirically determine that this model can be applicable to the frequency of 5.41 GHz used in these measurements.
4.4.3 Comparison with 802.11ax channel model

As indicated in section 2.2.4.5, the overall indoor path loss for 802.11ax can be modeled using Equation 4.3. The indoor path loss in the same floor is described by Equation 4.4 [15].

\[
PL_{overall} = PL_{indoor}(d) + PEL_{floor} + PEL_{wall}
\]

Equation 4.3

\[
PL_{indoor}(d) = \begin{cases} 
L_{FS}(d) & , d \leq d_{BP} \\
L_{FS}(d) + 35 \log(d / d_{BP}) & , d \geq d_{BP}
\end{cases}
\]

Equation 4.4

The 802.11ax model considers a two-slope equation determined by a breakpoint distance \(d_{BP}\). Considering the case of an indoor typical office building indicated in Table 2.1 in section 2.2.4.5, \(d_{BP}\) is 10 meters. The slope before \(d_{BP}\) is 2, which is the same value than in the free space case, and the slope after \(d_{BP}\) is 3.5.

In the case of the measurements performed in the DLC, the number of slopes in the path loss curve depends on the scenario. In the case when the transmitter is fixed in the energy lab in level 1B and the receiver moves along levels 1B, 1 or 2, there is no line-of-sight with the transmitter and only one path loss slope will be distinguished, as indicated in section 4.2.1.1. In the case when the transmitter is located in the hallway on level 1B or level 2B, as indicated in sections 4.2.2.1. and 4.2.3.1, respectively, two path loss slopes can be identified, since the propagation conditions change from line-of-sight to non-line-of-sight. The breakpoint distance \(d_{BP}\), which is determined by the layout of the building and the location of transmitter and receiver, is around 12 meters when the transmitter is on level 1B, as shown in Figure 4.7, and between 20 and 22 meters when transmitting from level 2B, as shown in Figure 4.16 and Figure 4.23.
In the measurements in the DLC, the path loss slope before $d_{BP}$ is approximately 1.7, due to the waveguide effect caused by the propagation along the hallway, which contributes to the propagation of the signal through continuous reflections on walls, floor and ceiling. The difference with the value of 2 in the 802.11ax model is because the latter does not consider the waveguide effect. Additionally, since the 802.11ax model will be designed to operate in both 2.4 and 5 GHz, the path loss values will vary depending on the frequency. As indicated in the indoor line-of-sight measurements performed by Cheung and Prettie [33], the path loss exponent for the ISM 2.4 GHz band is 1.91, which is close to the value of 2 indicated in the 802.11ax model. In the 5 GHz band, the path loss slope is 1.83 for the U-NII-1 band, 1.72 for the U-NII-2 band and 2.15 for the U-NII-3 band. Since the operating frequency in our measurements is 5.41 GHz, we are closer to the U-NII-2 band, according to the 5 GHz U-NII frequency ranges indicated in section 2.1, and the path loss slopes in both cases are 1.7.

The path loss slope after $d_{BP}$ is approximately 4.5 in our measurements, which differs from the value of 3.5 indicated in the 802.11ax channel model. Cheung and Prettie [33] also determined that the path loss slope in non-line-of-sight conditions is 3.73 in the ISM 2.4 GHz band, 4.7 for the U-NII-1 band, 4.48 for the U-NII-2 band and 4.59 for the U-NII-3 band. The path loss slope of 4.5 obtained in our measurements agrees to the value for the U-NII-2 band. Additionally, as in the case of line-of-sight conditions, the path loss slope indicated for the 802.11ax model is closer to the path loss for the ISM 2.4 GHz band than the one for the U-NII-2 band.

As also indicated in section 2.2.4.5, the indoor floor penetration is calculated using Equation 4.5. Considering a fixed transmitter and a receiver moving along levels 1B, 1 and 2, we estimate the floor loss depending on the floor separation $n$ between transmitter and receiver.
\[ PEL_{\text{floor}} = 18.3n^{((n+2)/(n+1))-0.46} \]  \hspace{1cm} \text{Equation 4.5}

Table 4.4 shows that the loss due to propagation through floors is 18.3 dB considering 1 floor separation, 33.5 dB for 2 floors separation and 43.6 dB for 3 floors separation. Note that the loss per floor decreases with the floor separation. In our measurements, we obtained floor attenuations of around 20 dB, which do not differ much from the case of one floor separation using the 802.11ax model. In order to determine more accurately the attenuations due to floors, more measurements in different buildings should be performed.

Table 4.4. Cumulative loss for different floor separations according to the 802.11ax channel model

<table>
<thead>
<tr>
<th>Number of floors between transmitter and receiver (n)</th>
<th>PEL_{floor} (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.3</td>
</tr>
<tr>
<td>2</td>
<td>33.5</td>
</tr>
<tr>
<td>3</td>
<td>43.6</td>
</tr>
</tbody>
</table>

The indoor wall penetration for the 802.11ax channel model is calculated using Equation 4.6, where \( m \) is the number of walls penetrated and \( L_{iw} \) is the penetration loss for a single wall.

In our measurements, we obtained values of \( L_{iw} \) between 5 to 10 dB.

\[ PEL_{\text{wall}} = m * L_{iw} \]  \hspace{1cm} \text{Equation 4.6}

In the outdoor to indoor scenario of the 802.11ax model, the path loss is calculated using Equation 4.7, also described in section 2.2.4.5. It considers an in-building penetration loss of 20 dB, which is indicated in the equation.

\[ PL_{\text{outdoor-to-indoor}} = PL_{\text{outdoor-NLOS}} (d_{out} + d_{in}) + 20 + 0.5d_{in} \]  \hspace{1cm} \text{Equation 4.7}

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In our measurements, we obtained an approximate value of 25 dB for the loss through external walls and windows. This value is similar to the 20 dB considered in the 802.11ax model and it depends on the building materials and structure.

In conclusion, some path loss parameters considered in the 802.11ax model are similar to the ones obtained in our measurements, but some of them are also different because of the frequency considered and the layout of the buildings studied.
CHAPTER 5

5 CONCLUSIONS AND FUTURE WORK

As part of this work, we have performed measurements of 5 GHz mobile radio channels for fixed to mobile configurations in different scenarios using a novel narrowband measurement system. The measurements enabled us to estimate the channel parameters, from which we can derive conclusions and propose future directions on this topic.

5.1 Conclusions

We can infer significant conclusions about the novel measurement system used and the 5 GHz mobile channel characteristics for the conditions studied in this work.

First, the novel measurement system has proved to be highly precise, stable and versatile for characterizing the mobile radio channel. In contrast to a wideband channel sounder, this narrowband system acts as a moving probe that transmits a continuous wave signal, without the need of high bandwidth available and with the additional advantage of being more immune to interference. The data acquired is sampled at audio frequencies and, since the in-phase and quadrature components are extracted, it permits many signal processing options, which reinforce its flexibility and convenience for future propagation and interference studies.

Also, the system permits to accurately characterize the mobile 5 GHz radio channel for indoor and indoor to outdoor environments in a representative office building. The baseband complex data acquired enables us to calculate the path loss, first-order statistics and also the Doppler power spectrum, which is a great advantage of this system. The Doppler information permits to study the scattering environment and understand the mechanisms involved in mobile
channel propagation. For example, it was possible to study the effect of the foyer area and interior walls by analyzing each of these parameters, as described in this work.

The values of the mobile radio channel parameters for the environments studied depend on the structure and distribution of the building measured. The path loss depends on the distance between transmitter and receiver and is influenced by shadowing caused by obstruction from objects. The Doppler shift is caused by the relative movement of the receiver from the transmitter and the multipath environment. The Doppler power spectrum has a dominant frequency component if there is a specular component and, in that case, the fading will be expected to have a Rician distribution. If the signal is very diffused, many signal components arrive at the receiver, which causes the fading to have a Rayleigh distribution. Also, it was observed that in outdoors environments, the value of the k-factor is much higher because the signal suffers less reflection. The more scattered the signal, the lower the k-factor value.

The path loss parameters estimated from the measurements are comparable to the ones obtained in previous propagation studies in similar conditions. The values of some of these parameters are also similar to the ones that will be considered in the 802.11ax model, but some of them differ due to the structure and layout of the building measured and because 802.11ax will operate in the 2.4 GHz band, in addition to the 5 GHz band that we are measuring. According to our measurements, the signal loss per interior wall is between 5 to 10 dB, the loss per floor is approximately 20 dB and the in-building penetration is around 25 dB. The path loss slopes are also consistent with measurements of other researchers [22]-[35]. According to the measurements, in case there is a waveguide effect, the slope is approximately 1.2, while in regular in-building LOS conditions is 1.7 and, for obstructed in-building propagation, it is around 4.5. The attenuation factor model [11] can be applicable for empirically modeling the indoor path
loss in the 5 GHz band. This model considers the addition of attenuation factors due to walls and floors, which were calculated in the measurements.

Finally, the data obtained permits to understand the 5 GHz mobile channel for future spectrum sharing capabilities and design considerations for deployments of WiFi and LTE-U networks. It provides an estimation of the attenuation factors and path loss exponents expected in an office building in this frequency band, how the signal is scattered in the environment and which fading distribution is expected for each section of the building. By describing the electromagnetic interactions of the signal with the environment, it will be possible to implement effective diversity techniques in order to counter the fading in the multipath channel.

5.2 Future work

Based on the results presented in this work, some additional work can be done in order to extend the scope of the channel characterization and perform further studies in mobile propagation in different environments and bands.

It will be interesting to perform additional measurements in other frequencies in the 5 GHz band and in residential buildings and outdoor environments as well. This will provide valuable complementary information to the one obtained in this work that will permit to characterize the propagation in this band in a more extensive way.

Another future task consists on determining the impulse response of the multipath channel, which can be done using a wideband channel sounder. The multipath channel can be modeled as a linear filter with time varying impulse response [1], since the different components of the signal arrive at the receiver with different amplitudes and delays. This channel characteristic will permit to calculate the delay spread of the channel, which is the difference
between the time of arrivals of the first and last multipath component. The coherence bandwidth can be calculated from the delay spread and it is inversely proportional to it. It determines the bandwidth over which two frequency components will be correlated in amplitude [1]. These parameters will permit to characterize the multipath nature of the channel for different propagation conditions.

Finally, using this measurement system, it will be interesting to design a plan on how to implement spectrum sharing between WiFi and LTE considering the propagation characteristics and multipath effects on the signal, which will depend on the movement of the receiver and the scattering environment. Additionally, it will be interesting to perform interference studies in the 5 GHz band near the places where meteorological and military radars operate in order to provide suggestions about how they can coexist with WiFi and with the proposed LTE-U.
BIBLIOGRAPHY


[33] D. Cheung and C. Prettie, “A path loss comparison between the 5 GHz UNII band (802.11 a) and the 2.4 GHz ISM band (802.11 b),” *Intel labs*, 2002.

