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Small handsets performances for 4G LTE

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Preface

First we would like to acknowledge Samantha Caporal Del Barrio and Mauro Pelosi our supervisors for their support and recommendations during this semester.

The theoretical capacity of the MIMO wireless channel and the impact of different antenna parameters on it such as correlation has been characterized in previous studies. The goal of this study is to analyze the variations and interaction of several parameters which have an essential impact on the optimization of antennas design on small handset with different use cases. To do this we will use data collected by simulations and also by a measurements campaign provided by Aalborg University. This report is structured in six chapters, i.e. the first two are introductive chapters to the problem, the following three chapters present the results of the measurements and the last one sums up the conclusions.

Abstract

In this study we analyze how to optimize antenna diversity system on small handset design. The evolution of the use of the mobile phone with a constant need for higher capacity on small device has raised new challenges in the handset and antennas design. Our main objective is to investigate different parameters affecting the overall efficiency of an antenna system on a small handset. In fact today customers can use their phones in data mode not only to send messages but also to download data or watch video in streaming for example. This development has induced new ways to use and hold the phone. The different user's interactions can in some cases strongly impact the efficiency of the overall system. This is why we will study the influence of the user on antenna parameters like correlation, mean effective gain, branch power ratio, power received and channel capacity variations.

Our analysis and conclusions are based on simulations results and also on results coming from measurements campaign done from Aalborg University in downtown Aalborg in 2011. We have proceed by first extracting the data then clustering it by groups parameters, computing statistical analysis, and analyzing the impact of each of them on the overall antenna design.
Based on the results in the simulation part we have observed for the two handsets studied that the user decreases the correlation, the mean effective gain and the power received in θ polarizations in each channel models considered (TAGA, AAU and Isotropic). In the measurements' analysis we have analyzed parameters variations of ten handsets with different antennas design in eight common use cases that an user may experience plus a study of the SAM and hand phantom performance. We have noticed a confirmation of the negative impact of high correlation on the MIMO capacity performance. We also characterized which antenna design is more sensitive to reach such high correlation. Moreover the branch power ratio impact on the channel capacity performance is limited. In a further work different level of signal to noise ratio and different antenna combining techniques should be experienced.

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List of Acronyms

Acronym	Description
AWGN	Additive White Gaussian Noise
BFF	Big Form Factor
BPR	Branch Power Ratio
BS	Base Station
CDF	Cumulative Distribution Function
CSI	Channel State Information
DL	Down-Link
DMFL	Data Mode Flat
DMLL	Data Mode Landscape Left Tilt
DMLR	Data Mode Landscape Right Tilt
DMP	Data Mode Portrait
EM	Electromagnetic
EGC	Equal Gain Combining
FG	Firm Grip
FS	Free Space
GP	Ground Plane
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HSPA	High Speed Packet Access
IFA	Inverted F Antenna
KPI	Key Performance Indicators
LA	Local Average
LH	Left Hand
LOS	Line of Sight
LRHL	Landscape Mode right tilt left hand only
LRHR	Landscape Mode right tilt right hand only
LRTH	Landscape Mode right tilt two hands
LTE	Long Term Evolution
MEG	Mean Effective Gain
MIMO	Multiple Input Multiple Output
MRC	Maximum Ratio Combining
MS	Mobile Station
OFDMA	Orthogonal Frequency-Division Multiple Access
OH	One Hand
PHR	Portrait Mode Right hand only
PIFA	Planar Inverted F Antenna
PTH	Portrait Mode Two hands
QoS	Quality of Service
RH	Right Hand
SAE	System Architecture Evolution
SAM	Specific Anthropomorphic Mannequin
SC	Selection Combining
SC-FDMA	Single Carrier - Frequency Division Multiple Access
SFF	Small Form Factor

SINR	Signal-to-Interference-plus-Noise Ratio
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SNR	Signal-to-Noise Ratio
SG	Soft Grip
SQ1	Square 1
TH	Two Hand
TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power
UL	Up-Link
UMTS	Universal Mobile Telecommunications System
XPD	Cross-polarization discrimination
XPR	Cross-polarization power ratio

1 Introduction

The area of the wireless communication began in 1895, when Guglielmo Marconi demonstrated the possibility of using radio wave to communicate over long distance. Today the mobile phone market achieves one of the fastest expansion in the telecommunications area. It is currently representing the biggest percentage of the new subscription in the world. Since the beginning of this decade the number of mobile phone subscribers has become higher than the conventional one [1]. In most of the world region, the mobile phone expansion is superior of one hundred percent and the market is still growing. According to the last information given by the Wireless Intelligence (WI) and the GSM association focused on the wireless market, the world new subscription growth is currently of 40 millions.

With the fast development of wireless communications all over the world and the evolution of the network and the mobile devices to fit user needs in term of high transmission and reception capacity, the telecommunications industry has to face new challenge such as high data rate, signal reliability to decrease the signal loss and multipath fading effects but also power requirement due to miniaturization of the mobile handset.
The evolution in wireless technology will have a big impact on the telecommunications, changing the way of people can access to information and interact with each other through their mobile devices. The focus of the network operators is especially on data mode because the need of the customers to check the web, download/upload data or for example watching a video in streaming wherever they are is growing up very fast. 4G could be the answer to the request of the customers of wireless broadband access anytime and anywhere [1]. Actually this evolution of the wireless communications is carried by the Long Term Evolution (LTE) technology and its evolution LTE-advanced. LTE is a pre-4G standard whose goal is a broadband network which can improve the performance of the UMTS/HSPA standard. LTE allows to provide the users a greater achievable capacity, higher downlink/uplink data rates for wireless and wired connection with OFDMA access scheme in downlink and SC-FDMA in uplink, very low latency and especially a much higher throughput with respect to the previous technologies. LTE allows also to obtain a better overall operational efficiency of the network for the operators with System Architecture Evolution (SAE). Moreover in case of no coverage the LTE technology of the mobile phone is able to switch to the previous technologies networks, i.e. it can work on GSM or UMTS bands exploiting their networks [2].
LTE technology exploits the use of Multiple Input Multiple Output (MIMO) systems especially for improving the signal reliability. Indeed using several antennas in reception diminishes the probability to have a low signal strength at the receiver. In the past years there were multiple antennas only at the base station. With the evolution of the technology it has been possible to use multiple antennas also at the receiver side with different form factor like mobile phone, laptop, tablet. Multiple antennas system which depend of the number of receiving and transmitting antennas allowed to strongly increase the capacity with some peak of downlink capacity of 4 by 4 MIMO system three times superior than SISO[2].

As we can see on the fig. 1.1 different systems can be created in function of the number of transmitters or receivers. In this work we will mainly study MIMO system with two transmitters and two receivers. MIMO system allows to exploit the path diversity in which one radiated path may

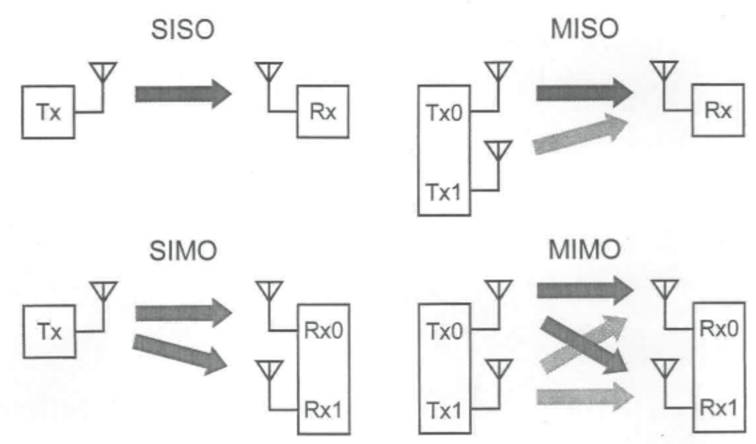


Figure 1.1: Different communication systems

suffer from fading loss instead another path may not be affected. A second advantage of MIMO is to be able to steer the beam of the radiation pattern in order to get the best signal or to transmit more radiated power in a particular direction. Several combining techniques can be exploited to achieve a better reception of the signal. MIMO performance which is basically measured by is ability to obtain higher capacity depends on several parameters value like correlation, Mean Effective Gain (MEG) or Branch Power Ratio (BPR). Implementation of several antennas in a mobile handset has increased the complexity of their impact on the efficiency of the overall system. Actually integrating multiple antennas on a mobile device has revealed several design challenges such as physical size, type, resonant frequency, positions of the antennas, bandwidth etc. In fact the use of MIMO systems on small handsets involves smaller distance in terms of wavelength between antennas which can increase the mutual coupling.

Therefore in a mobile phone or in general in handheld device the antenna plays a fundamental role. The antenna is that component that transforms an electrical signal into an electromagnetic wave [4]. Since the appearance of the first mobile phone to nowadays the antenna has undergone deep changes becoming more complex because of the evolution of mobile communications. The reasons of these changes are different: improving the quality of service(QoS) and antenna's performances, reducing the power absorption in user's body, need for more bandwidth, etc.. [5].
The first antenna was a half wavelength monopole. Then the evolution in technology brought to integrated antennas like the Inverted F Antenna(IFA). Currently the most used antenna in mobile phones is the Planar Inverted F Antenna or PIFA. It is an evolution of IFA where the radiating element is not a wire anymore but a plane. One of the reasons for which this antenna is common is its ability to work in different frequency bands of the different network standard as GSM, LTE, UMTS etc. On a mobile phone there are several antennas, each for a specific application as Wi-Fi, Bluetooth, GPS, transmission and reception. In a LTE/MIMO context the antennas mounted on the device have to be small due to the reduced size of the phone and be able to work so close to each other.

In general the behavior of a handset antenna can be analyzed looking at several key performance indicators(KPIs). In this study we concentrate on MEG, received power, correlation between antennas, BPR and capacity in order to have an overall understanding of the handset's performances. The impact of the user on these parameters will be investigated. The goal of this report is analyze the performances of several handsets operating in 4G-LTE network finding out which one has the best design.

Antenna efficiency is a measure of how good the antenna is performing. This parameter is expressed in dB or percentage. Ideally it would be 100% but it never reaches this value because of the losses such as body losses, dielectric power losses, mismatch losses, ground losses. Since it is not possible to provide the direction of the incoming signal the use of dipole antennas could be a good choice because it is omnidirectional. Thus for an antenna as the dipole the efficiency is a good indicator because it doesn't take into account the direction of radiation [6].
The MEG is an important parameter to describe antenna's performances of a mobile handset. It is deduced from the radiation patterns of the considered channel models [7] which, for this project are the isotropic model , the Taga model and the AAU one. All these three models will be described in the next chapter (section 2.8). The influence of each channel on the performances of the handsets is analyzed in the study of the simulation results.
The MEG is a measure of the average received power from the considered antenna referred to the total average received power of a reference antenna, usually isotropic. The MEG is a more realistic parameter than others such as efficiency or total radiated power(TRP) for the up-link(UL) and total isotropic sensitivity(TIS) for the down-link(DL) because it considers also direction and polarization characteristics of both handset and channel. Considering different environments and different mobiles, the performance varies largely because of the orientation of the mobile in the considered scenario. Using the TRP or the TIS it is not possible to evaluate these variations because they do not consider the orientation. That is why the MEG is more realistic. An antenna is good when it maximizes the MEG in the environment [8],[9].
The BPR is indicated when multiple antennas are involved(MIMO system). This KPI is related to the MEG. Indeed it is the ratio between the MEGs of two antennas and furthermore according to the analysis done in [8] the BPR experiences dependence on the orientation of the device. The BPR allow to indicate the level of MEG differences between branches of a MIMO system. Therefore according to which diversity combining techniques is used the level of BPR will impact the diversity gain achievable.
The correlation between antenna is an important parameters especially with MIMO system. It is defined as the ratio between the average received signal gain and the angle of arrival of a signal. We can deduce that a rich multipath propagation scenario diminishes the correlation. Indeed the multipath propagation spreads the signal and thereby several components are received from different directions. A higher correlation will lead to more dependent branches between receiver and transmitter reducing the diversity gain achievable. Then it is important for MIMO system that the correlation between antennas keeps low (under the threshold of 0.5) in order to obtain the maximum of benefits from the the diversity gain [10].

These parameters are related to two main characteristics of antennas which are the radiation pattern and the power distribution of the environment. The power distribution has a key role in the computation of these parameters and most of the time it is considered to be isotropic. Such model is unrealistic but can be defined as a reference and allows mathematical simplification. However the majority of propagation measurements has proved that the power in the environment is most of the time directive or clustered. Therefore the power distribution models are mostly based on measurement campaign and statistics [11]. In this study we will also consider the AAU model which was developed on large scale measurement campaign in downtown Aalborg. It is an outdoor to indoor propagation model. The Gaussian power distribution model known as the Taga model [11] is also considered. The power distribution have a Gaussian shape bell in elevation and uniform distribution in azimuth.

Antenna KPIs undergo also the influence of the user since the mobile handset is, in most of the cases, close to the user. In some cases the user can directly interact with one antenna or several ones depending on the handling. Modern use of mobile phone in data mode involved new ways to hold the phone and hands interaction. Consequently parameters such as correlation, MEG or BPR can be strongly impacted by the user interactions. In the analysis of the performances it is fundamental to take into account the user's impact, i.e. phantom user but also real user. Otherwise all the tests done on a device are not complete and thus not realistic. Only after having done all the necessary tests it is possible to state that the phantom can replace the real user if the results confirms it. This is the kind of problem happened to the Iphone 4 of Apple which had some reception issues when it was released [12], [13]. More deep tests in presence of the real user could have avoided the problem.
The user causes losses in the power radiated by the antenna because he absorbs part of it. In particular the head and the hands are the parts of the body that mainly affect the antenna in a mobile handset. Since we consider a PIFA, according to [14] this type of antenna has a head loss between $5dB$ and $7dB$ in the low band and between $2dB$ and $4dB$ in the high band. Considering also the losses due to the hand, there is an increase between $1dB$ and $5dB$ in both the bands. Since the mobile phone is always more used for browsing or in general in data mode, it is necessary to take into account several positions of holding the handset because each position has a different impact on antenna performance. In this project we consider two kind of grips regarding the simulation part: firm and soft. See figures 5.9 and 5.10 in the appendix for more details on the two grips. For the measurements data more specific handset's modes are available like portrait and landscape with one or two hand including the tilt. After having evaluated and compared their influence, all the handset modes will be compared with the free space case where the user is not considered. Even considering only the free space there could be differences of several dBs between handsets' performances due to their different designs and the different characteristics of their antenna system.

1.1 Problem definition

As stated previously the reduction of the handset size, the need for capacity and the evolution of the use of the mobile device involve new challenges for antenna designer. Moreover the reliability of a MIMO system working on a mobile phone depends on the variation of different parameters such as the correlation, MEG, BPR, power received and channel capacity. The goal of this thesis is to investigate several handsets to see which ones have a good antenna design to experience better overall performances and what design choice has what consequences on the antenna performances. The analysis is based on the data collected from a simulation and the data collected from measurements campaign. In this way a comparison between simulated and realistic data is possible.

1.2 Outline

The report is structured in the following way. Chapter 2 deals with theoretical knowledge. In this chapter all the theoretical informations used later in the report are presented. Chapter 3 presents the measurements campaign characteristics and the different handsets involved. Chapter 4 shows the results obtained from the simulation for two handsets and the analysis of the different parameters involving antenna design. In chapter 5 we will use the data collected from the measurements for ten handset in different use case and handling in order to analyze the performance of each handsets according to different parameters variations. Moreover a comparison with the results shown in chapter 4 will be provided. To conclude we will present a summary of our work and conclusions on antenna design performances.

2 Theoretical Background

2.1 Planar Inverted F Antenna

A PIFA is an antenna in which the radiating element is a plate. It derives from an IFA(Inverted F Antenna) where the the radiating element is a wire. The PIFA presents a short pin between the patch and the ground plane(GP). The presence of the pin implies that the antenna is shorted at the end. Hence the size of the patch is reduced of a factor $1/2$ although it keeps its property of half-wavelength patch. Reducing the size of the shorting plane allows to decrease the resonance frequency. The resonance frequency is $\lambda/4$ but without the shorting pin this resonance frequency is not possible.

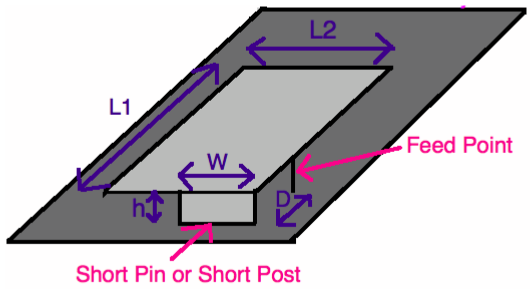


Figure 2.1: The Planar Inverted-F Antenna [4]

The resonance frequency is given by this equation [15] :

$$L_1 + L2 = \frac{\lambda}{4} \tag{2.1}$$

When $W = L2$ then $L1 = \frac{\lambda}{4}$. When $W = 0$ then $L1 + L2 = \frac{\lambda}{4}$.

Since the resonant frequency depends on the length of the short pin then reducing W means reducing the resonant frequency.

A PIFA has several advantages as reducing the SAR(Specific Absorption Rate), increasing the gain in horizontal and vertical polarization, and reducing the size of the antenna due the shorting pin. The PIFA is currently the most common antenna used in the smartphone with built-in antenna or portable devices because of its reduced size, simple structure, easy design and low costs. Moreover with a PIFA it is possible to implement several frequency bands [16] and it shows sensitivity to both polarizations of the electromagnetic wave, i.e. sensitivity to the device's orientation [17].

2.2 Q-factor and bandwidth

An important parameter for an antenna is the Q-factor or quality factor. It is defined as the ratio between the power in the reactive field of the antenna and the radiated power [3]

$$Q = \frac{2\omega \cdot max(W_M, W_E)}{P_{rad}} \tag{2.2}$$

where ω is the angular frequency, W_E the electric energy, W_M the magnetic energy and P_{rad} the radiated power. The two energies coincide at the resonant frequency.
It can be also defined as the ratio between the carrier frequency of the antenna and its bandwidth [4]. Hence it is a way to define the bandwidth.

$$Q = \frac{f_c}{\Delta f} \tag{2.3}$$

Equation 2.3 shows an inverse proportionality between the Q-factor and the bandwidth. Hence an antenna with high Q will have a narrow bandwidth while an antenna with low Q will have a wide bandwidth.
Considering a high-Q PIFA there are several ways to increase the bandwidth. One of this is to reduce the size of the ground plane [18]. Moreover the bandwidth can be broadened modifying the radiating element of the PIFA. Besides study in [19] demonstrates that the widths of feed element and shorting pin can increase the bandwidth up to 65% . Another way is to add a rectangular slot into the GP and then changing the position and the dimensions of the slot allows to have a GP of similar size of the considered low and high bands [20].
It is important to notice that the PIFA we will consider later in the report for handset 11 and 12 is tunable [21] thus a small bandwidth is enough to cover one channel.

2.3 Smith Chart

The Smith chart is a graphical tool very useful to see the matching of an electrical circuit. The Smith chart is represented on the reflection coefficient plane that is a unit radius circle. On it is possible to visualize the impedance of the load of the circuit. Looking at the value of the load impedance we are ideally able to match it with the impedance of the line, that is 50Ω. In practice is not always possible to erase the imaginary part of the impedance. Hence the goal is to try to have a real impedance, ideally of 50Ω, or at least as close as possible to this value. When the impedances are matched means that the curve that represent the behavior of the impedance intersects the center of the chart which corresponds at the value $\Gamma = 0$. The horizontal diameter of the chart represents the line where the impedance is real. The circles inside the Γ plane are the locus of points where the real part of the impedance is constant. The curves departing from the right extreme of the unit radius circle and going towards the circumference of the circle represent the locus of points where the imaginary part of the impedance is constant. When the imaginary part is positive then the curve is in the upper half of the chart and this means an inductive behavior of the impedance. When the imaginary part is negative then the curve is in the lower half of the chart and this means an capacitive behavior of the impedance [22]. In figure 2.2 all the aspects of the Smith chart are shown.

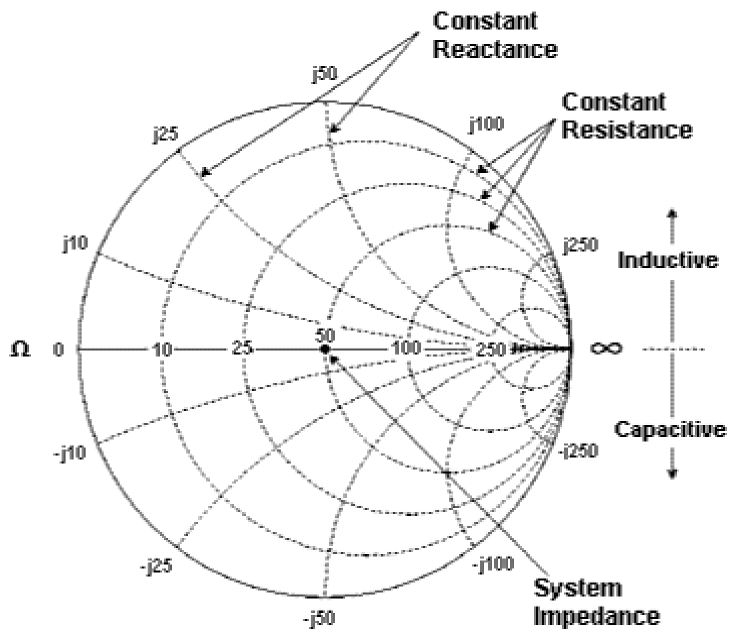


Figure 2.2: Smith chart [22]

2.4 Antenna efficiency

Usually the term antenna efficiency is referred to the antenna radiation efficiency which gives a perception of the losses occurring in the antenna. The radiated power can be expressed by this formula [4]:

$$P_{rad} = \oint_{AV} P_{AV} dS = \oint_{AV} \frac{1}{2} Re[E \times H^*] dS \tag{2.4}$$

where P_{AV} is the time-averaged Poynting vector. E and H are the electric and magnetic field vectors (amplitudes). The radiated power can also be defined as [4]:

$$P_{rad} = P_{max} - P_{tloss} = P_{av} - P_{diss} - P_{body} - P_{emb} \tag{2.5}$$

Where: P_{max} is equal to the maximum power available at the antenna input,P_{tloss} is the total power loss,P_{diss} is the Ohmic and dielectric power loss, P_{body} is the power absorbed in the human body, P_{emb} is the power dissipated in other antennas trough mutual coupling.

The power absorbed by the user P_{body} is the normal component of the time-averaged Poynting vector integrated over the surface of the lossy scatterer(user) [4].

$$P_{body} = \oint_{S_{SCAT}} P_{AV} dS_{scat} \tag{2.6}$$

Therefore we can defined the antenna efficiency as the ratio of the radiated power to the total available power of the antenna:

$$\epsilon_{rad} = \frac{P_{rad}}{P_{in}} \tag{2.7}$$

Which is also equal to:

$$\epsilon_{rad} = \frac{P_{rad} + P_{body} + P_{diss} + P_{emb}}{P_{in}} \tag{2.8}$$

It is a value between 0 and 1 but it is usually expressed in percentage or in dB. When an antenna has high efficiency means that most of the power is radiated while when the efficiency is low means that most of the power is lost, e.g. absorbed or reflected.

Actually the radiation efficiency is only a part of the overall efficiency of the antenna, i.e. the product of the radiation efficiency and the antenna's loss due to the impedance mismatching.

$$\epsilon_{tot} = \epsilon_{rad} \cdot M_L \tag{2.9}$$

Obviously $\epsilon_{tot} = \epsilon_{rad}$ if there is no impedance mismatching. Hence M_L greatly influences the total efficiency of an antenna.

2.5 Mean Effective Gain and Branch Power Ratio

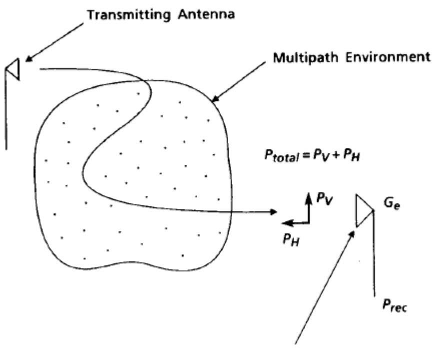
As stated in chapter 1 the MEG is the ratio between the average received power by the antenna and the overall average incident power received by a reference antenna that is moving randomly in the same environment. It represents how a mobile device transmit and receive power in a realistic environment. Furthermore it is a good parameter to characterize the Rayleigh fading because it coincides with the average power [23].

$$G_e = \frac{P_{rec}}{P_{ref}} \tag{2.10}$$

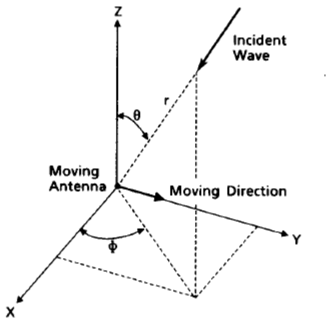
This parameter is very important to explain the antenna behavior because it takes into account characteristics of the real environment and also the directional and polarization properties of the antenna. Hence to compute the MEG it is important to know the propagation properties of horizontally and vertically polarized components of the incident waves. According to [11] the equation becomes :

$$G_e = \frac{P_{rec}}{P_V + P_H} \tag{2.11}$$

where P_V is the mean incident power in θ polarization and P_H is the mean incident power in ϕ polarization.



(a) Average power arriving at receiving mobile antenna in multipath environment [11]



(b) Spherical coordinates in mobile radio environments [11]

T. Taga in [11] found a closed formula to express the MEG in spherical coordinates :

$$G_e = \oint \left[\frac{XPR}{1+XPR} P_\theta(\Omega) G_\theta(\Omega) + \frac{1}{1+XPR} P_\phi(\Omega) G_\phi(\Omega) \right] d\Omega \tag{2.12}$$

where XPR is the cross-polarization ratio, that is the ratio between P_V and P_H. $P_\theta(\Omega)$ and $P_\phi(\Omega)$ are respectively the power in θ and ϕ polarization. $G_\theta(\Omega)$ and $G_\phi(\Omega)$ are the radiation patterns for each polarization. $P_\theta(\Omega)$ and $P_\phi(\Omega)$ follow these conditions:

$$\oint P_\theta(\Omega) d\Omega = \oint P_\phi(\Omega) d\Omega = 1 \tag{2.13}$$

The gains are normalized such that :

$$\oint \left[G_\phi(\Omega) + G_\theta(\Omega) \right] d\Omega = 4\pi \tag{2.14}$$

Typically a value for the MEG of a 100% efficient antenna in an isotropic model is $-3dB$. Naturally isotropic model is not a realistic situation, thus the MEG value can change of few tens of a dB or more than $1dB$ if the antenna efficiency decreases. Obviously the value changes also considering another model, a more realistic one [8].

The MEG is a parameter describing a single antenna case. When multiple antennas are considered(like MIMO,SIMO or MISO) then the BPR is more indicated. It is the ratio between the mean effective gains of two considered antennas. It is usually expressed in dB and can be derived from this formula [8]:

$$BPR = 10log_{10}\frac{MEG_A}{MEG_B} \tag{2.15}$$

where MEG_A and MEG_B are the mean effective gain of antenna A and antenna B respectively considering the total power normalized. Hence the BPR and the MEG are strictly related to each other. Since the MEG takes into account the orientation of the mobile handset, the BPR will be dependent on it, e.g. data mode portrait and data mode landscape have a different impact [8].

2.5.1 MEG Optimization

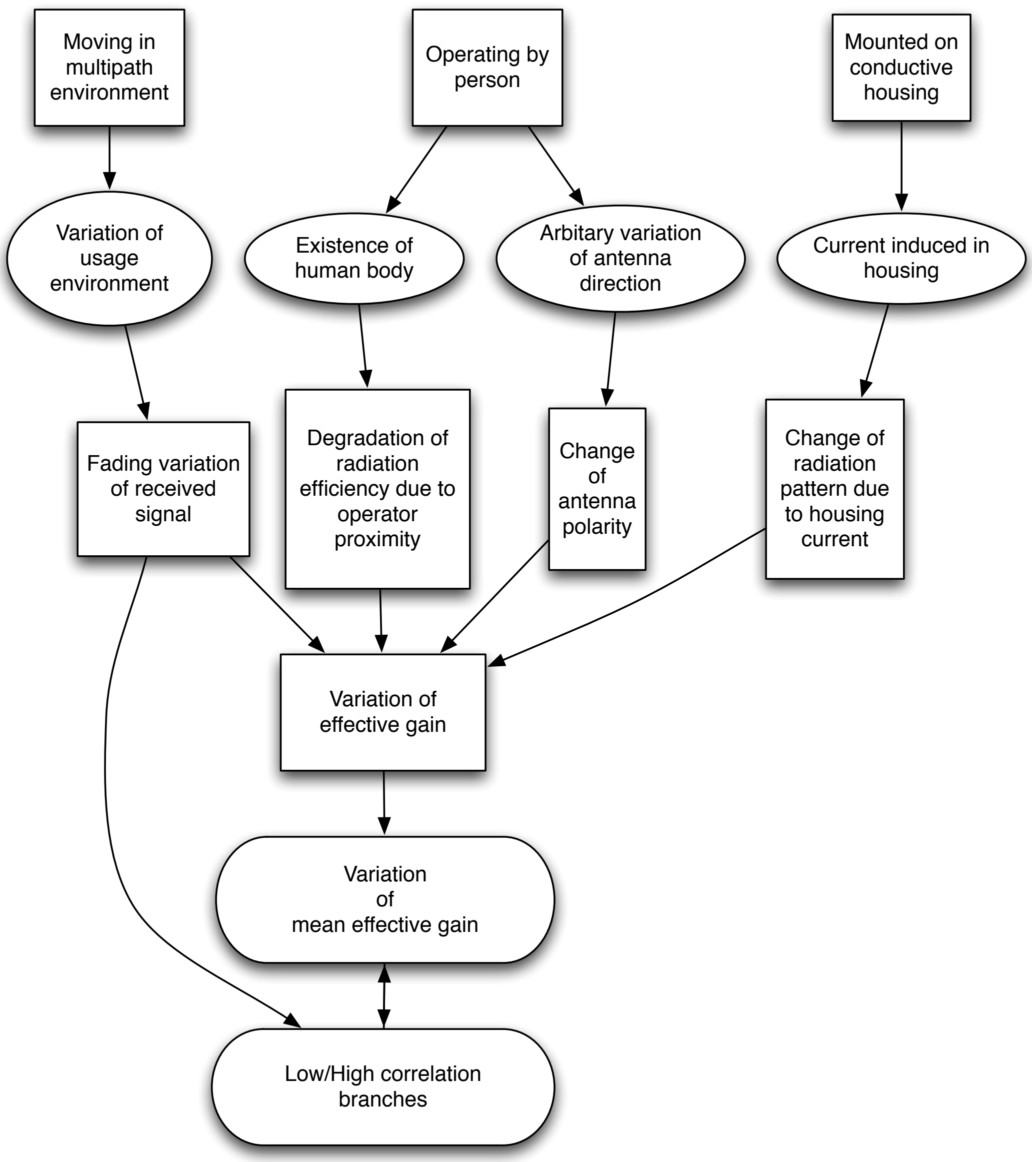


Figure 2.3: Environment and parameters variations impacting the MEG [28] [23] [11]

As we can expect the MEG is subject to strong variation. In the plots above we summarize these parameters interactions on the mean effective gain such as multi-path environment, user interaction and conducting housing [28] [23] [11]. All these handsets and environmental parameters involve some change on the way the average power is received at the antenna receiver. Moreover it has been experienced that low correlation allows to optimize the MEG [28] and a higher one has a negative impact on the MEG. In the measurements and simulation part we will meet such environmental and handset interaction which can explain MEG and BPR difference observed between different use cases and handset configurations.

2.5.2 Antenna correlation

Correlation between antennas indicates the degree of relation between the antennas of an antenna system. We can formulate it by this equation [24]:

$$\rho = \frac{R_{xy}}{\sqrt{\sigma_x^2 \sigma_y^2}} \tag{2.16}$$

Where R_{xy} is the cross covariance between two antennas x and y, σ_x and σ_y are the standard deviations of the received signal.

The cross covariance is defined in this way [24]:

$$R_{xy} = \oint [XPR\vec{E_{\theta X}}(\Omega)\vec{E^*_{\theta Y}}(\Omega)\rho_\theta(\Omega) + \vec{E_{\phi X}}(\Omega)\vec{E^*_{\phi Y}}(\Omega)\rho_\phi(\Omega)]d\Omega \tag{2.17}$$

In this equation $\vec{E_{\theta X}}$ means the electric fields for the antenna X and for θ polarization. ρ_θ means the power distribution in a θ polarization. Then Ω indicates spherical variation in θ and ϕ.

With XPR defined as the cross polarization of the environment : $XPR = \frac{Polarized Power in \theta}{Polarized Power in \phi}$.

We can also formulate the variance σ of an antenna i by:

$$\sigma_i = \oint [XPRG_{\theta i}(\Omega)\rho_\theta(\Omega) + G_{\phi i}(\Omega)\rho_\phi(\Omega)]d\Omega \tag{2.18}$$

With $G_{\theta i}$ represent the gain patterns for the antenna i in θ polarization.

The envelope correlation ρ_e is the correlation between the envelops of two signals. Clarke's approximation allows to relate envelope correlation and correlation [25] and it has been also demonstrated that $\rho_e = \rho_p$ where ρ_p is the power correlation. It is an approximation because the phase is not taken into account. Therefore ρ_e in a Rayleigh fading model is obtained by squaring the absolute value of the antenna correlation:

$$\rho_e \approx |\rho|^2 = \frac{|R_{xy}|^2}{\sigma_x^2 \sigma_y^2} \tag{2.19}$$

Since in practice it is not possible to compute the correlation of complex fields this formula allows to measure the magnitudes [25]. Antenna correlation is between -1 and 1 therefore the envelope correlation will be between 0 and 1.
We will consider now an isotropic distribution which means an uniform power distribution on the sphere for the azimuthal and elevational polarizations. By consequence the power polarized in ϕ and θ will be the same and the cross polarization power ratio XPR will be equal to 1. This model allows to make simplifications in the formulation of the correlation in function of the XPR. A high spatial correlation means that some directions are stronger than others and a low spatial correlation means the same signal from all the directions can be expected. We can deduce that the propagation of a signal in a multipath environment decreases the spatial correlation. In fact multipath environment spreads the signal such as several multipath components come from different directions.

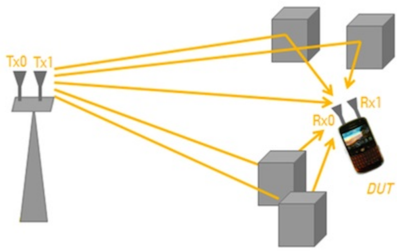


Figure 2.4: Multipath MIMO environment [14]

The need for capacity over the last years has given birth to MIMO system that is able in to increase the theoretical capacity fixed by the Shannon formula in a multipath environment. However, a high spatial correlation in MIMO system can reduce the performance of multiple antenna systems[26]. We can deduce that a high spatial correlation will decrease the number of independent channel. Therefore a high correlation decreases the improvement in diversity gain which rely on independent signals. A study on the effects of envelope correlation on diversity gain [27] shows that if $\rho_e \leq 0.5$ we are able to express the degradation on the diversity gain by this factor

$$DegradationFactor, DF = \sqrt{1-\rho_e} \tag{2.20}$$

2.6 User Influence

As mentioned in the introductive chapter the presence of the user affects antenna performance. It has been studied [28] that the hands(fingers and palm), which are in the reactive near-field region, can cause a significant effect on the effiency of the antenna. The body causes mostly shadowing effect in the radiating near-field (Fresnel) and/or in the far-field (Fraunhofer) regions.
A parameter which can explain this phenomenon is the body loss(BL). The body loss is defined as the mean total power gain of an antenna in free space to the total power gain of an antenna in presence of the user [28].

$$BL = 10log_{10}\frac{G^{FS}}{G^{user}} \tag{2.21}$$

The BL considers the power absorbed by the human body and thereby the radiated power lost by the antenna can be quantified. Low values of BL may depend on the position of the antenna, e.g. top of the mobile handset. Instead reasons for high values of BL could be the de-tuning of the antenna and its position, at the bottom in this case. Hence handsets with antenna placed at the bottom have higher BL. When a handset has antennas at the top and at the bottom the average difference in BL between the two antennas is around $5.5dB$ [28].
In general the antenna in a mobile device is influenced by the user and consequently all the performance parameters will vary respect to the free space situation. The presence of a user will affect both the correlation coefficient and the MEGs (branch powers). As the diversity gain depends on the combining method and the probability level chosen in most of the cases this means a decrease in the performance but there are cases where the presence of the user is worth. Indeed in the low frequency band of short antennas, despite the body absorbs radiated power creating losses, it can be considered as radiating element and this implies an increase in the antenna efficiency [29].

2.7 Diversity Systems

Diversity gain is the gain when there are several receiving antennas and a combining scheme is used at the reception side. EM (Electromagnetic) waves can meet moving and fixed obstacles on their trajectory. These obstacles scatter the signals creating multi-path and producing deep fade at the receiver. In order to provide a good reception of the desired signal the receiver asks for a new path to the transmitted signal with a sufficiently high SNR. A secondary branch allows to increase the probability that the strength of the received signal is high. Uncorrelated or slightly correlated diversity branches below the threshold of 0.5 have less chances of experiencing a deep fade in the same time. This point highlights the need of MIMO system to reach low correlation between branches. We will study correlation impact in the chapter 4 and 5. As explained the diversity is reached by using the information on the different branches known to the receiver in order to increase the SNR at the receiver side. Therefore having more branches increases the probability that one branch or more once combined together produces a sufficiently high SNR to allow reliable decoding of the message at the receiver even more with an low correlation. Consequently in order to obtain a diversity gain we need to produce diversity branches [30] .

2.7.1 Diversity Branches

Additional diversity branches can be generated in different ways like antenna, time, and frequency. The main problem of producing diversity branches using time and frequency is that additional system resources are required instead of antenna diversity. That's why we will be focused on antennas diversity. Antenna diversity requires multiple antennas at the receiver and is therefore extremely dependent on the handset design. However, operating at high frequency band and improvement in handset and antenna design allows to obtain multiple antennas not only at the base stations but also on the mobile handset. Antenna diversity can be achieved through several way: spatial, polarization, or by using pattern. Spatial diversity is the most common of the three and requires two or more antennas to be separated in space at the MS. Two antennas that are physically separated in space and low correlated experience different propagation environments and multi-path components sum differently at each antenna. If the antennas are spaced far enough the branch signals have a higher probability to experience fading independently. That's why antennas location and handset size have an important impact on the diversity gain achieved with spatial diversity.

2.7.2 Diversity combining techniques

Several techniques for using or linking diversity branches in order to improve the system performance exist. Thanks to different combining techniques, we can combine received signals of several branches to obtain a more reliable received signal. Basically the combined signal $y(t)$ received by the system is represented by:

$$y(t) = \sum_{n=1}^{N} w_n^* u_n(t) \tag{2.22}$$

$$With : u_n(t) = h_n(t)x(t) + n_n(t) \tag{2.23}$$

N is the number of receiving antennas, w_n^* the conjugate of the weighting coefficient, $u_n(t)$ is the received signal with noise $h_n(t)$ is the channel response, $x(t)$ is the transmitted signal and $n_n(t)$ is the noise at the n^{th} system branches.

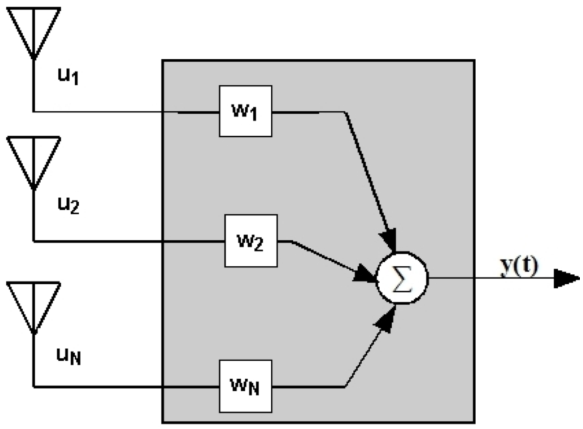


Figure 2.5: General combining of received signal for multi-antenna system [31]

Several combining techniques exist more or less linear or complex allowing to received a reliable signal. The main ones are selection, equal gain and maximum ratio combining respectively (SC, EGC and MRC). When the SC is chosen, the receiver checks the SNR of all branches and choose the information from the branch with the highest SNR [32]. In comparison with AC EGC and MRC are not only using the signal coming from one branch as output signal. Therefore the mean power of the output signal is optimized by using signal combining coming from all the branches. With EGC the receiver simply makes a coherent sum of the received signals to increase the SNR at the receiver side [32]. The most effective of these three techniques is MRC [33], [34] basically because the SNR at the receiver is the sum of all SNRs of the different branches. One of the disadvantage of MRC is that it needs channel state information(CSI) for its estimation. It is fairly unrealistic to have a perfect estimation in a real system but the gains of this technique can be approached as well.

2.7.3 Diversity Gain

Diversity gain, is a measure of the gains achieved from a system using diversity scheme. Diversity gain depends of several parameters such as envelope correlation, branch SNR distribution, number of branches, combining technique. In order to measure the benefits of diversity gain we can define the cumulative distribution function of a Rayleigh channel by [27]:

$$P(\gamma < \gamma_s) = (1 - e^{\frac{\gamma}{\Gamma}}) \tag{2.24}$$

where Γ is the mean SNR, γ is the instantaneous SNR, $P(\gamma < \gamma_s)$ is the probability that the SNR will fall below the given threshold, γ_s.

With N independent branches we can assuming that each branch has independent signals and equal average SNRs. The probability of all branches having a SNR below γ_s is equal to the probability for a single branch raised to the power N as in [27]:

$$P(\gamma < \gamma_s) = (1 - e^{\frac{\gamma}{\Gamma}})^N \tag{2.25}$$

2.7.4 Factors affecting the diversity gain

There are several factors which affect strongly the diversity gain such as the phone environment which has a strong impact on the envelope correlation between the branches of a system and also the BPR. Antennas are placed about at half a wavelength apart or less due to size limitation and this separation might be too small to obtain low correlation. Measurements show that the coupling can be significant for a separations less than half a wavelength changing the antenna patterns of both elements [35]. Most of the diversity schemes improves the SNR but in some cases it can perform worse. This mainly happens with EGC technique when more noise than signal is received [34] thus the study of MEG and BPR is important to monitor the diversity gain.

2.8 Channel propagation model

Several type of distribution models have been proposed by different researchers. Each propagation models are specific and design to fit to different locations and environments studied. In the simulation analysis we studied mainly three different models: Isotropic,Taga and AAU models.

2.8.1 Isotropic model

Due to its power distribution the isotropic model is the most unrealistic one. Indeed it has uniform distribution on a sphere either in elevation either in azimuth polarization. It means that the power does not depend on the polarization but is constant [24]. This model can be described with a cross-polarization discrimination $XPD = 0dB$ and $P_\theta = P_\phi = 1/4\pi$. Although it is not realistic is mostly used as reference environment [8].

2.8.2 Taga model

This model has been defined by Tokio Taga [11] to be used in a typical mobile communication urban or suburban environment with most of the incident waves have been diffracted, reflected or scattered by building or surrounding objects. As the environment has no specific rules depending of the buildings parameters of each place it can be stated that the incident waves arrive at the antenna over a random route. It is assumed that the angular density functions in vertical and horizontal polarized waves is uniform in azimuth. However measurement results [11] indicate that for the angular density function in the elevation angle for the horizontal polarized P_ϕ and for the vertical polarized one P_θ follow a Gaussian distribution model. This is the reason why this model is also called Gaussian model. Then the distribution functions of incident plane waves are expressed as follow:

$$P_\theta(\theta, \phi) = A_\theta e^{-\frac{[\theta - [(\frac{\pi}{2}) - m_V]]^2}{2\sigma_v^2}} (0 \leq \theta \leq \pi) \tag{2.26}$$

$$P_\phi(\theta, \phi) = A_\phi e^{-\frac{[\theta - [(\frac{\pi}{2}) - m_H]]^2}{2\sigma_H^2}} (0 \leq \theta \leq \pi) \tag{2.27}$$

With m_V and m_H the mean elevation angle of each vertical and horizontal polarization wave distribution from the horizontal direction are equal to zero in the Taga simulation model. σ_H and σ_V are the standard deviation of vertical and horizontal polarization respectively. Their value is 30^o for both. A_θ and A_ϕ are constant. Also for this model $XPD = 0dB$ [8].

2.8.3 AAU model

This model defined in [36] is more focused on the interaction between an outdoor BS and an indoor MS. This is the most common interaction in a urban area today. Such model takes into account the interaction of the building on the distribution of the signal. Actually most of the energy in this environment comes from opening space in the building such as windows. However some signals come also from the wall penetration or reflection. It has been proved [36] that we can consider for those signals a uniform distribution but their powers are weaker. By decreasing the impact of the weaker signals we can deduce that the overall signals are not uniformly distributed like in a outdoor-outdoor environment but more clustered. From the measurements it has been found that the XPD for this model is equal to $5.5dB$ [36].

2.9 Channel Capacity

In this part we are interested to define the capacity of the different channels existing (MIMO,SIMO and SISO) and to compare their efficiency without any CSI. The theoretical capacity given by the Shannon formula is also considered since it is the expectation of the capacity with a perfect channel and coding.

2.9.1 SISO Capacity

We defined a SISO system with h the gain of the channel, and γ the SNR of the receiving antenna therefore the capacity without CSI is in bps/Hz [37]:

$$C = log_2(1 + \gamma|h|^2) \tag{2.28}$$

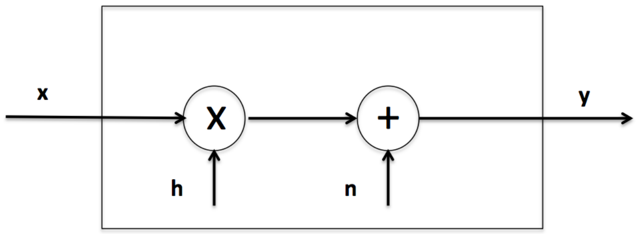


Figure 2.6: SISO system

Moreover the theoretical capacity will be:

$$C_t = E(C) = log_2(1 + \gamma E(|h|^2)) \tag{2.29}$$

with $E(|h|^2) = 1$ thus the theoretical capacity becomes:

$$C_t = log_2(1 + \gamma) \tag{2.30}$$

The capacity is increasing in function of the logarithm of $1 + \gamma$. When the SNR is high, a gain of 3dB on the SNR will therefore increase the capacity of 1 bps/Hz.

2.9.2 SIMO Capacity

A SIMO system is defined by one transmitting antenna and N receiving antennas with h_i the complex gain between the emitting antenna and the i^{th} receiving antenna.

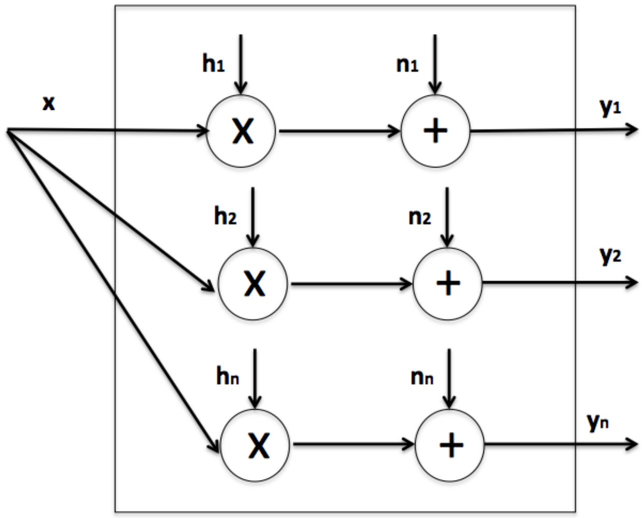


Figure 2.7: SIMO system

We can therefore define the SIMO capacity by [37]:

$$C = log_2(1 + \gamma \sum_{i=1}^{N} |h|^2) \tag{2.31}$$

Therefore Shannon capacity will be:

$$C_t = E(C) = log_2(1 + \gamma N^2) \tag{2.32}$$

With $\sum_{i=1}^{N} |h|^2 = N^2$.

The capacity in SIMO system will increase faster than a SISO one.

2.9.3 MIMO Capacity

For a MIMO system with M emitting antennas and N receiving antennas we can define the transmission mode [33] by:

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{pmatrix} = \begin{pmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N,1} & h_{N,2} & \cdots & h_{N,M} \end{pmatrix} \cdot \begin{pmatrix} L_{p1} \cdot x_1 \\ L_{p2} \cdot x_2 \\ \vdots \\ L_{pM} \cdot x_M \end{pmatrix} + \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_N \end{pmatrix} \tag{2.33}$$

With $y_1 \ldots y_N$ the received signal with N antenna elements from M transmitters $x_1 \ldots x_M$ coming after going through complex channels $h_{i,j}$ which is the complex gain of the channel between the j^{th} emitting antennas and the i^{th} receiving antennas. $\mathbf{H}$ represents only the small-scale differences, while the large-scale pathloss for each transmitter are expressed by the values $\mathbf{L_p} = L_{p1} \ldots L_{pM}$. Noise is represented by the vector $\sigma = \sigma_1 \ldots \sigma_N$.

We can define the capacity of a MIMO system in [bps/Hz] by [37]:

$$C = log_2(det[I_N + \frac{\gamma}{M} HH^H]) \tag{2.34}$$

When N and M are big, the expectation of the capacity for a Rayleigh channel increase proportionally with the number of receiving antennas N. $E[C] \approx Nlog_2(1+\gamma)$. Therefore depending on N and on the SNR the capacity is increasing faster than SIMO or SISO system (See: figures 2.8 and 2.9).

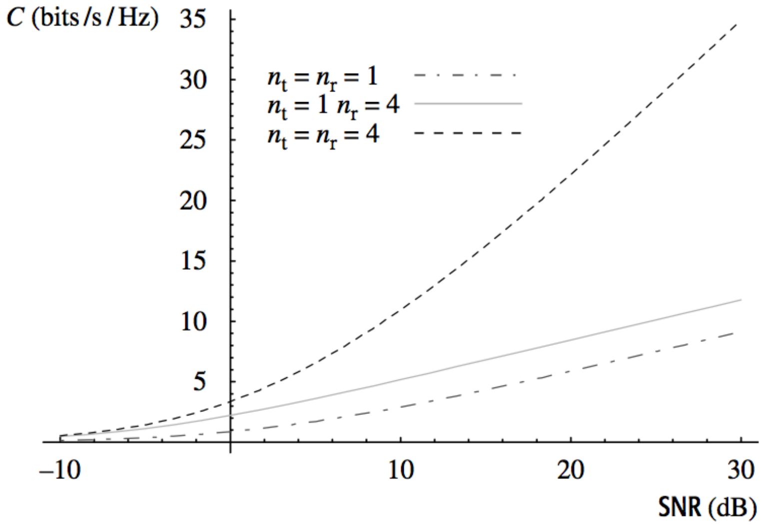


Figure 2.8: Capacity depending on SNR with SISO, SIMO and MIMO systems. [31]

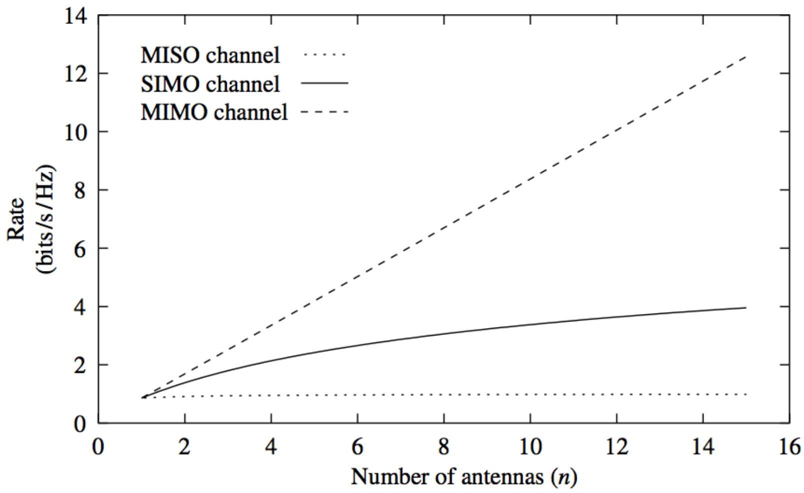


Figure 2.9: Capacity of the n by 1 MISO channel, 1 by n SIMO channel and n by n channel with SNR = 0dB [31]

3 Experimental Data

3.1 Environment description

3.1.1 Measured site

The measurement site takes place inside Aalborg university building located downtown in Aalborg, Denmark. As described in the section about the AAU model the propagation is outdoor-to-indoor in an urban environment. The room is a square of sides A-B-C-D each one four meters long. It is shown in figure 3.1 where the arrows represent the user orientation. Each user with a specific handset walks forward and backward along one side of the square, twice for every measurement. Different types of user interaction are combined with several handsets in different location of the room in order to make all the measurements. In the middle of the room a cable holder was ensuring that the optical fiber do not twist. For the low band we can estimate by using wavelength formula $\lambda = \frac{c}{f}$ that for 16 meters of measurement we obtain around 40λ of sounding distance and around 120λ for high band. In order to make simplification we will consider the four sides of the room as one general indoor case.

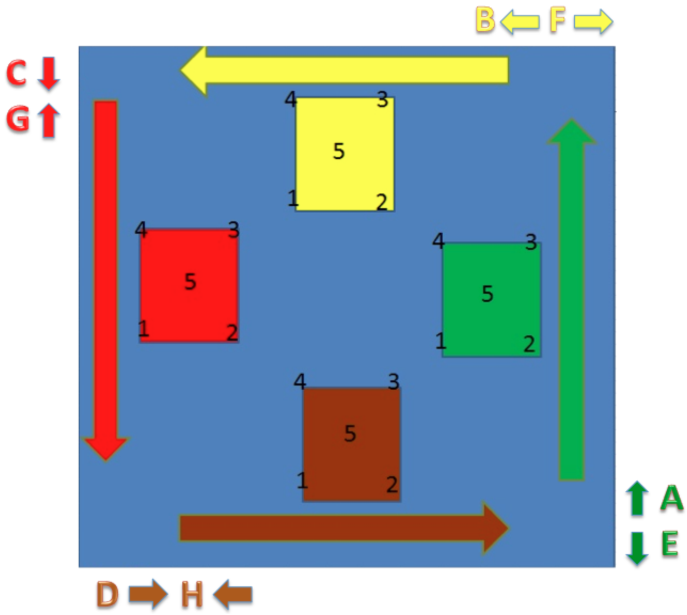


Figure 3.1: Modelization of the measurement room

The model has been verified by statistical basis by making data sets of spherical power spectrum measurement using four BSs sites and four indoor MSs locations. In this report only the two near BSs will be considered. Then the performance of the MS including users interaction have been investigated by twelve users. A correlation sounder was linked to the horn antenna in order to record the vertical and horizontal polarization simultaneously and the sampling interval was five degrees.

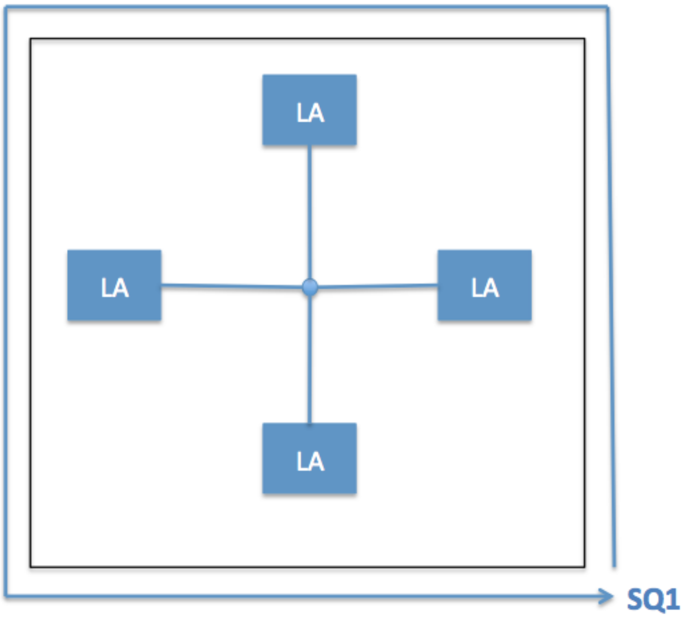


Figure 3.2: SQ1 and LA measurements

One measurement lasts 20 seconds whether it is LA or SQ (fig. 3.3), the numbers 1 to 4 mean $1/4$ of $20s = 5s$.

(a) LA measurements

(b) SQ1 measurements

Figure 3.3: LA and SQ1 measurements

Measurement Uncertainties

When the design and the specification of the setup have been done for measuring the performance of mobile devices, we have to take into account the accuracy of the resulting measurements. In fact equipment needs to be calibrated, either separately or combined. However, even a calibrated system can give results within a certain margin of errors due to issues such as measurement noise. Some examples of error sources in measurements can come from: properties changes due to temperature differences at calibration time and measurement time, variation due to different connectors, reflection in anechoic room, incorrect mounting of mobile device, errors due to insufficient sampling of radiation pattern or thermal noise [24].

3.1.2 Handsets

By studying the influence of the handset's characteristics on KPI such as correlation, MEG, received power and BPR we are then able to rank the devices. That's why in this study we will analyze ten handsets with different characteristics. The main differences between them are the form factor, antenna type, antennas location on the handset and their resonant frequencies. For simplicity in a first time we will be focused on the H11 and H12 differences by using results comings from simulations and measurements. In this case the form factor influence of the handsets on the efficiency parameters can be investigated since it is the only difference between the two. Then by using the data collected from the measurements for the other handsets we will have an overview of all the handsets. The characteristics of these handsets are described in the table below.

Handset	Form Factor	Antenna	Antenna Location	Antenna Type	Resonant Frequencies
H1	PDA Type 111x59 mm	1	Bottom	Single feed ILA	Low and High Band
		2	Top	Single feed ILA	Low and High Band
H2	PDA Type 111x59 mm	1	Top right long side	Single feed MAC (LISF)	Low and High Band
		2	Bottom right long side	Single feed MAC (LISF)	Low and High Band
H3	PDA Type 111x59 mm	1	Top right long side	Single feed MAC (LISF)	Low and High Band
		2	Bottom right long side	Monopole	High Band
H4	PDA Type 111x59 mm	1	Top	Single feed ILA	Low and High Band
		2	Top right long side	Monopole	High Band
H5	PDA Type 111x59 mm	1	Top left long side	Single feed MAC (LISF)	Low and High Band
		2	Top right long side	Single feed MAC (LISF)	Low and High Band
H6	PDA Type 111x59 mm	1	Top	Single feed ILA	Low and High Band
		2	Left side	Single feed MAC (LISF)	Low and High Band
H11	PDA Type 111x59 mm	1	Top	PIFA	Low and High Band
		2	Bottom	PIFA	Low and High Band
H12	Bar Type 100x40 mm	1	Top	PIFA	Low and High Band
		2	Bottom	PIFA	Low and High Band
H13	PDA Type 111x59 mm	1	Top -Left	Helix	Low Band
		2	Bottom - Left	Helix	Low Band
H14	Bar Type 100x40 mm	1	Top-Left	Monopole	Low Band
		2	Top-Right	Monopole	Low Band

Table 3.1: Handsets characteristics

The design of H11 and H12 has been evaluated with an optimized software to the measurement characteristics using a FDTD method and then confirmed by measurement in an anechoic chamber [24]. Handsets 11 and 12 have two dual band antennas located one at the top and one at the bottom of the handset's ground plane. The antenna type experimented for these two handsets is a dual band PIFA, fig. 3.4, which resonates at $796MHz$ in low band and $2300MHz$ in high band. The two handsets were equipped of optical fiber allowing to measure antennas coupling and also of plastic material with a dielectric constant ε of 3 and a thickness of 1.5 mm [21].

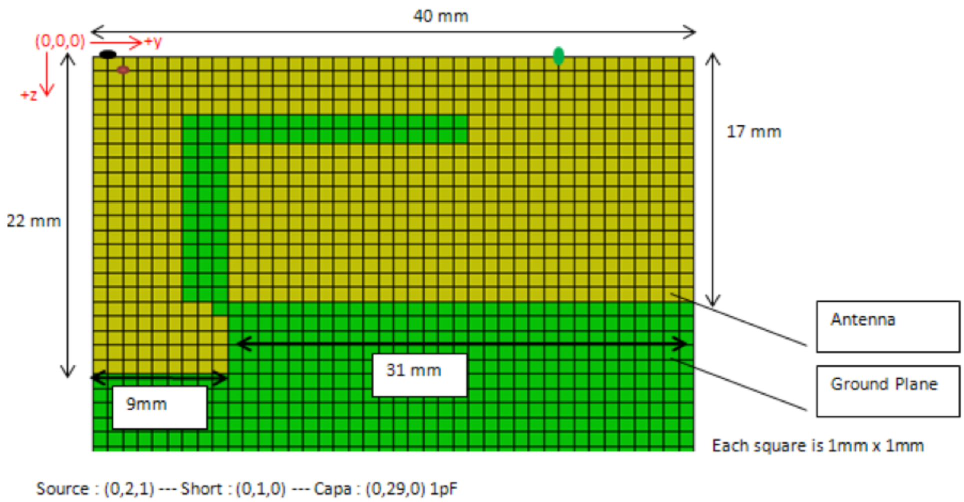
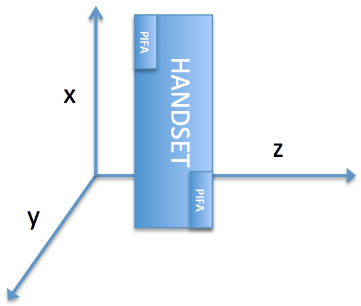
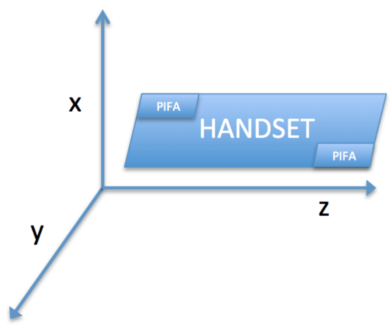


Figure 3.4: 100x40mm handset design. PIFA for H12

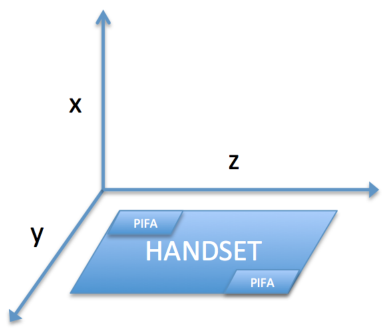
In the different measurements coming from the software the handset is considered in several positions. In free space we have flat, portrait and landscape mode. With the user interaction we experienced in our study different way of holding the phone using right, left or two hands in portrait or landscape mode(Figure: 3.5).



(a) Portrait mode



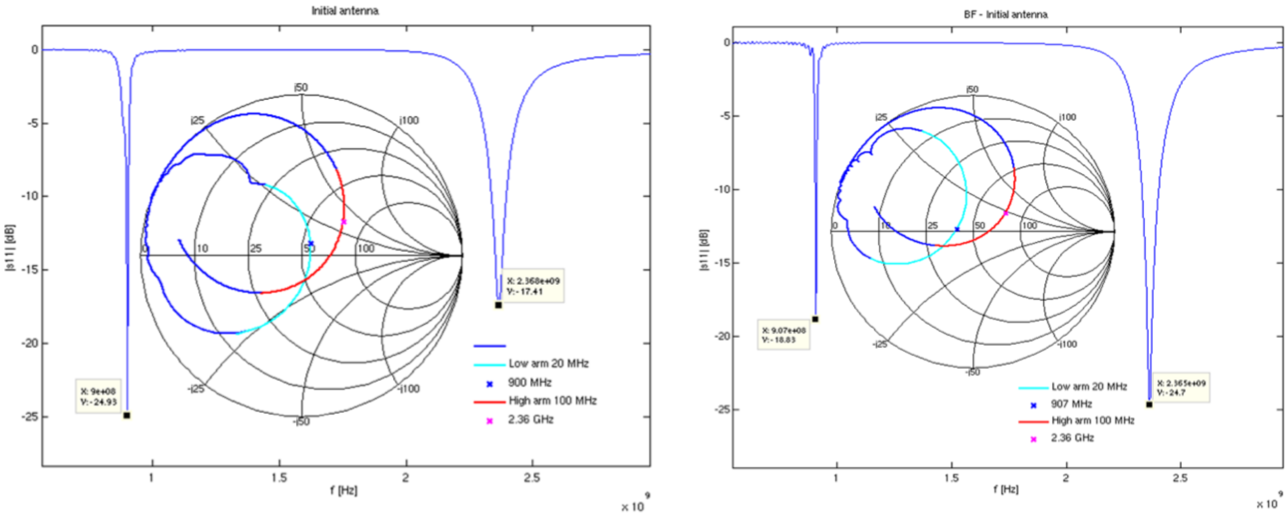
(b) Landscape mode



(c) Flat mode

Figure 3.5: Handset handling

In table 3.1 we can see that the only difference between H11 and H12 is the size of the GP. H12 is considered as a Small Form Factor(SFF) with a size of 100x40 mm^2 whereas H11 is considered as a Big Form Factor(BFF) with a size of 111x59 mm^2. However by studying the smith chart (3.6) coming from the two different handsets we can observe differences. The S_{11} parameter which basically represents how much power is reflected from the antenna shows at which of the two resonant frequency(796 MHz and 2300 Mhz) the handset is more efficient.



(a) 100x40mm Handset (b) 111x59mm Handset

Figure 3.6: Smith chart of H12 and H11

Fig. (a) is for H12 and fig. (b) is for H11. H12 presents less reflected power in low band since S_{11} is lower. For H11 the situation is exactly the opposite. Less power is reflected in high band. On the Smith chart we can observe the trend of the load impedance in function of the frequency. For both the handsets in low band the impedance fits better with the ideal value of 50Ω that is the impedance of the line. Comparing the two handsets in high band we observe that the BFF handset(H11) is closer to 50Ω.

4 Simulation

4.1 Correlation between antennas

In this section the correlation between top and bottom antenna of each handset is computed and analyzed. An increase in correlation implies a decrease in SNR and consequently in MIMO capacity. Therefore the correlation study is a key factor of the antenna efficiency.
In the next table the results obtained for handset 12 and 11 for each channel and use case are summed up. The table shows for both the bands not only the mean value but also the minimum and the maximum values in order to see the variation of the correlation. Moreover the difference between the mean values of the two bands, $\Delta\rho_e$, is shown to underline the difference between them. The mean values have been computed as follow for both handset and for each channel model. In the low band three frequencies are considered 788MHz, 796MHz and 805MHz whereas in the high band they are four 2250MHz, 2300MHz, 2350MHz and 2400MHz. Therefore the mean envelope correlation for the low band is simply the mean of the envelope correlation of the three frequencies and for the high band it is the mean of the envelope correlation of the four frequencies.

Handset	Use Case	Channel	Low Band	High Band	$\Delta\rho_e$
H12	Free Space	Isotropic	0.1/0.5/0.9	0/0.1/0.2	0.4
		Taga	0.3/0.6/0.9	0/0/0.1	0.6
		AAU	0.6/0.8/0.9	0/0/0.1	0.8
	Firm Grip	Isotropic	0.1/0.1/0.1	0/0/0.1	0.1
		Taga	0.2/0.2/0.3	0/0/0.1	0.2
		AAU	0.3/0.4/0.4	0/0/0.1	0.4
	Soft Grip	Isotropic	0.4/0.4/0.5	0/0/0.1	0.4
		Taga	0.6/0.6/0.7	0/0/0.1	0.6
		AAU	0.8/0.8/0.8	0/0/0.1	0.8
H11	Free Space	Isotropic	0.3/0.5/0.8	0.1/0.1/0.1	0.4
		Taga	0.5/0.6/0.8	0.1/0.1/0.2	0.5
		AAU	0.6/0.7/0.9	0.1/0.2/0.2	0.5

Table 4.1: Envelope correlation - summary for H12 and H11

From the table we can see that the correlation is always higher in the low band due to the lower distance between the antennas. In the low band free space and soft grip present, for all the channels, values higher than 0.5 which is the usual threshold used by the industries to identify a good correlation [24]. For the firm grip the antennas show a good correlation because it is always below the threshold. In the high band both the handset perform good because the correlation is always below 0.5. This means that in this band the handsets work better from the MIMO performance point of view. However we are more concerned in the low band because the wavelength is bigger due to the lower frequency and consequently the size of the antenna system is bigger in terms of λ. For $H12$ we observe how the influence of the user reduce the correlation. Especially the firm grip leads to a much lower correlation. In the analysis of the sounding data we will verify if the same situation is confirmed.

4.1.1 Comparison

The two handsets can be compared only in free space. $H12$ and $H11$ have the same general trend because the correlation tends to decrease going up with the frequency. Both the handsets has a high correlation in the low band which overcome the threshold of 0.5 thus they have a better MIMO performance in the high band where the correlation is always below 0.5. The difference between low and high band is about 0.5 for $H11$ and up to 0.8 for $H12$.
The form factor and the Q are the only differences between the two handset thus they are the only design parameter which could influence the correlation. In conclusion we can state that in free space $H12$ and $H11$ present the same envelope correlation, i.e. the distance between the antennas have no impact on the correlation and the quality factor as well. In the next chapter we will see if these results are confirmed with the measurements.

4.2 Mean effective gain

4.2.1 Results

We first consider the handset $H12$ and then the $H11$. After we will compare them. For both the handsets in the isotropic model whatever frequency and whatever location(top or bottom) we consider, the value of the MEG is always $-3dB$. This is what we expected because for the dipole the power is uniformly distributed on a sphere and the cross-polarization ratio is 1. Therefore the mean received power of the antenna and the total mean incident power will be constants. Hence only the Taga and the AAU models will be considered.
The table below shows the mean value of the MEG for free space(FS), firm grip(FG) and soft grip(SG) for each channel and for both handsets. For $H11$ there are only the values in free space in the table because the data for the user cases has been computed in a different way thus the comparison between H11 and H12 for soft and firm grip is not possible.

Handset	Channel	Antenna Location	Frequency[MHz]	$MEG_{FS}[dB]$	$MEG_{FG}[dB]$	$MEG_{SG}[dB]$
H12	Taga	Bottom	Low Band	-1.5	-1.9	-1.9
			High Band	-2.7	-3.2	-3.2
		Top	Low Band	-1.5	-2.1	-1.9
			High Band	-2.8	-3.3	-3.2
	AAU	Bottom	Low Band	-0.5	-1.2	-0.4
			High Band	-3.4	-3	-2.6
		Top	Low Band	-0.5	-1.5	-0.3
			High Band	-3.1	-3.9	-3.7
H11	Taga	Bottom	Low Band	-1.6	-	-
			High Band	-2.7	-	-
		Top	Low Band	-1.5	-	-
			High Band	-2.8	-	-
	AAU	Bottom	Low Band	-0.8	-	-
			High Band	-3.4	-	-
		Top	Low Band	-0.5	-	-
			High Band	-3.1	-	-

Table 4.2: MEG for handsets H12 and H11

The MEG can be basically defined like the ratio between the mean received power of the antenna and the total mean incident power (eq. 2.10) thereby it allows to measure the efficiency of the MS antenna in a multi-path environment [23]. Therefore also the MEG is a key indicator to determine the performance of the antenna. A value tending to 0dB means that the mean power received by the antenna coincides with the total incident power. The higher is the incident power with respect to the received power and the smaller is the MEG.
James and Fujimoto [14] have investigated that the MEG decreases when the antennas are smaller than 0.5 wavelengths because the radiation efficiency decreases due to the mutual coupling loss. Therefore reducing the space between the antennas close therefore reduces the efficiency as well as the correlation and so a compromise needs to be made. This point is verified by using the data coming from the simulation(Table: 4.2) and by computing the spacing between antennas in terms of wavelength. In the simulation study antennas for H11 are separated by a distance of 0.22λ for low frequency and 0.62λ for high frequency. For H12 antennas spacing is lower. It is equal to 0.18λ in low frequency and 0.50λ in high frequency. Moreover on the simulation we can see that the handset don't have an impact on the MEG as the results are very close. However we can observe strong differences between low and high band for the two models. Let's consider first the handset 12. For the Taga model the difference between the low and the high band is about $1.2dB$. This is valid for each use case(free space, firm grip and soft grip). Looking at the difference between FS and user cases we notice a difference of about $0.4dB$ either in low either in high band. For the AAU model the variation of the MEG between low and high band is $2.8dB$ for free space and soft grip while $2.2dB$ for firm grip. For the $H11$ the difference between low and high band is $1.2dB$ for Taga model and $2.1dB$ for AAU one. Therefore simulations results tends to confirme the influence of antenna spacing on the MEG. In fact when the antenna spacing is higher than $0,5\lambda$ for low frequency the MEG is higher than with an antenna spacing of $0,2\lambda$ achieved in high frequency. However the difference in terms of antenna spacing between the two handsets seems to be too low to have an impact on the MEG confirmed by the results which looks similar. On the table 4.2 we can also notice that antennas have very similar MEG values, which is ideal to achieve a high diversity gain. We can therefore assume

that, since the antennas are close, the local mean power levels available at the two branches are the same. In fact a maximum diversity gain will be obtained when the BPR is equal to one (eq. 2.15).

For both model the values are higher in low band due to the distance between the antennas. A big variation between the two bands has been observed in the AAU model. It is up to 3dB in free space and soft grip. Comparing the two channel models we noticed that the MEG does not change so much in the high band while in the low band the variation is up to 1.5dB. As soon as the user is involved in an active mode with the handset, in our case firm and soft grip, several phenomena happen. First the power can be absorbed (eq. 2.6) depending on the way the handset is held by the user [38]. Moreover polarization properties are changed and a strong shadowing can occur [38]. Therefore we can expect from the simulation less power received at the antenna which is confirmed by a lower MEG with user interaction than in free space.
In the Taga model the user decreases the MEG of 0.5dB for both top and bottom antenna whereas in the AAU model this variation is up to 1dB.

4.3 Received power

4.3.1 Results

We are considering the handsets $H12$ and $H11$ looking at the average power received in the two polarizations(P_{rec_θ}, P_{rec_ϕ}). The sum of the two gives the total received power(P_{rec}).

Channel	Use Case	Frequency Band	P_{rec_θ}[dB]		P_{rec_ϕ}[dB]	
			Top	Bottom	Top	Bottom
Isotropic	Free Space	Low Band	0.9	0.9	0.1	0.1
		High Band	0.6	0.6	0.4	0.4
	Firm Grip	Low Band	0.7	0.8	0.3	0.2
		High Band	0.4	0.4	0.6	0.6
	Soft Grip	Low Band	0.8	0.8	0.2	0.2
		High Band	0.5	0.5	0.5	0.5
Taga	Free Space	Low Band	1	1	0.1	0.1
		High Band	0.6	0.6	0.4	0.3
	Firm Grip	Low Band	0.8	0.9	0.2	0.2
		High Band	0.4	0.4	0.6	0.6
	Soft Grip	Low Band	0.9	0.9	0.2	0.2
		High Band	0.5	0.5	0.5	0.5
AAU	Free Space	Low Band	1.2	1.1	0.1	0.1
		High Band	0.5	0.4	0.4	0.4
	Firm Grip	Low Band	0.7	0.9	0.3	0.2
		High Band	0.3	0.5	0.7	0.6
	Soft Grip	Low Band	1.4	1.1	0.2	0.2
		High Band	0.3	0.5	0.7	0.6

Table 4.3: Received power for handset H12

H11 is not shown in the table because the received power is exactly the same of H12. Since the comparison is only in free space we expected this due to the similarities of the two handsets that cannot lead to relevant variations.

For all the channel models the power received in θ polarization is decreasing when the user is considered. The hand is in the near field of the antenna and it implies a great absorption of the incoming power [39]. In our case this absorption is not so evident since it is one or two tenths of a dB. In ϕ polarization an opposite situation is observed. The handset receives more power when the user is interacting with it. We can suppose that the user acts like a scatterer in this polarization and thereby more power is received when he is holding the mobile. Hence it seems that the user blocks more power coming from vertical polarization. Another difference between the two polarizations is that in θ the handset receives, as expected, more power in low band due to the lower attenuation. On the contrary in ϕ more power is received in high band.
It is also worth to notice that there are no big variations for top and bottom antenna either in FS either considering the user, i.e. the power received is not influenced by the location of the antenna on the handset.

Next two figures show the received power in the two polarizations in function of the frequency. Only the power received from the top antenna is showed since the values for the bottom antenna are close thus the curves have the same shape.

The blue plot identifies a ϕ polarization and the red one shows the θ polarization. We have to take into account that the total power received in free space in isotropic model has been normalized to 1 and that is why the power coming from the two polarizations oscillate between 0 and 1 dB. Since the two polarized powers come from the same use case they share the same total power received that is why we can observe a symmetry between them.

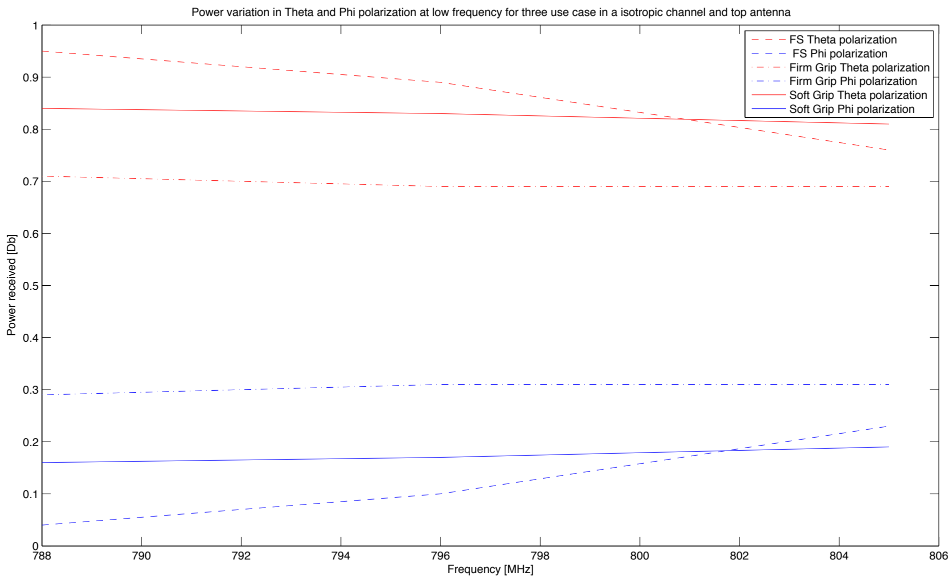


Figure 4.1: Power variation in Theta and Phi polarization at low frequency for the three use cases in isotropic channel. It's considered the top antenna of H12

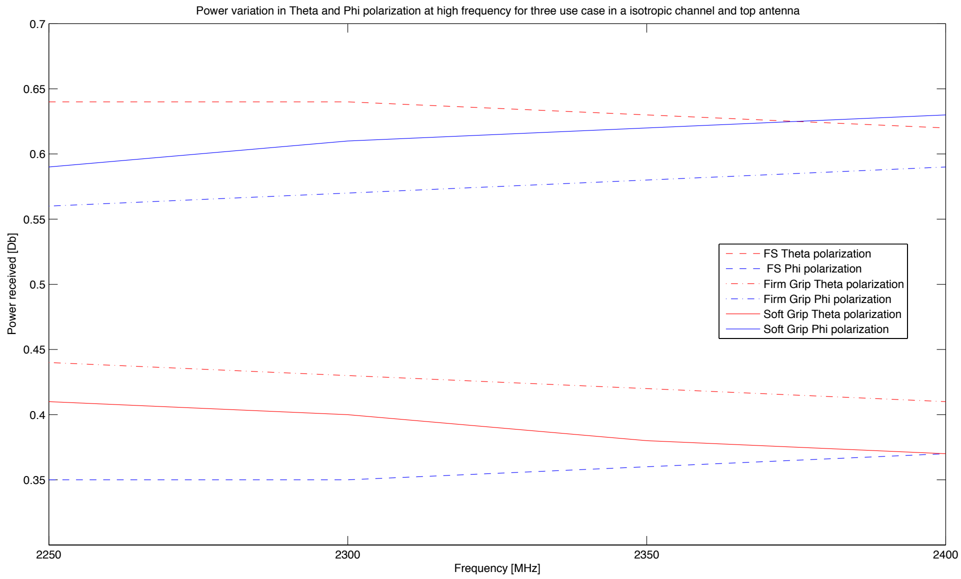


Figure 4.2: Power variation in Theta and Phi polarization at high frequency for the three use cases in isotropic channel. It's considered the top antenna of H12]l

We can see on plot (a) that for all the use cases with low frequency the power received in θ is higher than in ϕ. However we can observe that high frequency decreases the power received in θ. The difference between low and high band is between 0.3 and 0.6 for P_{rec_θ} and between 0.2 and 0.4 for P_{rec_ϕ}. This is valid for each channel model and for each handset. This particular point is due to the specific design of the dual-band PIFA antenna of the handset 12 for the high and low frequency. According to the Smith chart, fig. 3.6, the scattering parameters of the antenna at the same frequency are not equal. Therefore high and low frequency will not interact in the same way in terms of power received and can explain such difference in the polarization.

We can also notice the impact of the user on the power variation in θ and ϕ especially in high band where the received power in θ remains high in comparison of the user case.

5 Measurement

This chapter presents the results obtained from the sounding data and the consequent analysis.

5.1 Correlation between antennas

In this section the correlation data for each handset is analyzed. The correlation is not computed from the radiation pattern but obtained from indoor measured sounding data. In this way the data are more realistic than the one analyzed in chapter 4.
After having analyzed the correlation values in the different use cases(free space, user) and for each handset, a comparison between the handsets will be done. Furthermore a comparison between the data obtained from the measurements and the data obtained from the simulation is considered. Since only the data for H11 and H12 are available for the simulation, the comparison between simulated and measured data is done only for these two handsets.
For each analysis we always set these parameters in the software: only near base stations, indoor environment, all the locations in the room and all the users involved. Two frequency bands are considered. The low band represents the mean of all the three low frequencies while the high band represents the mean of all the four high frequencies. The seven frequencies are the same considered in the simulation.

First of all an analysis to see if the different measurement locations in the room can affect the results has been done. Chapter 3 explained that the measurements have been performed in local average(LA) or SQ1. The LA considers four different locations(A, B, C, D) in the room whereas the SQ1 considers the measurements have been realized moving the handset along the perimeter of the room.
By computing the mean envelope correlation of each handset in each of the four locations in the room, it has been found that in almost all the cases the mean envelope correlation is below the threshold of 0.5 and the variation in correlation is not so significant. This is valid for free space and in presence of the user. Hence although the location of the measurements can change a bit the value of the envelope correlation we can state that it has not an impact to be considered relevant. In really few cases analyzed(e.g. data mode portrait for H12, H1 or H14) changing the location leads to a correlation value that overcome the threshold or in general to relevant variations. As example it is shown the envelope correlation for the handset 12 but the same situation has been found for all the other handsets.

Side	Use Case	Frequency Band	Mean Envelope Correlation	
			Portrait Mode	Landscape Mode
A	Free Space	Low Band	0.5	0.3
		High Band	0.1	0.1
	Users	Low Band	0.3	0.4
		High Band	0.1	0
B	Free Space	Low Band	0.7	0.2
		High Band	0.1	0.1
	Users	Low Band	0.4	0.3
		High Band	0.1	0.1
C	Free Space	Low Band	0.5	0.4
		High Band	0.2	0.1
	Users	Low Band	0.3	0.3
		High Band	0.2	0.1
D	Free Space	Low Band	0.6	0.2
		High Band	0.2	0.1
	Users	Low Band	0.3	0.1
		High Band	0.1	0.2

Table 5.1: Mean envelope correlation for H12 for different locations in the room

For simplicity in the table portrait is referred to data mode portrait(DMP) in free space and portrait hand right(PHR) in user case whereas landscape is referred to data mode landscape right tilt(DMLR) in free space and landscape right tilt right hand only(LRHR) in user case. All the other types of handling lead to similar results. As we can see only in portrait mode changing the side leads to an increase in correlation which overcome 0.5 but in all the other situation the side does not have a relevant impact. For H1 and H14 the mean envelope correlation for each location is already above the threshold whereas for all the other handsets there are no cases at all in which changing the side in the room leads to overcome the threshold.

From this point we will not focus on the locations in the room but we will take into account only the mean of all the locations. This value will be very close or equal to the SQ1 measurements.

5.1.1 User influence

Before analyzing the envelope correlation values for each handset, the correlation of a "random" handset has been computed. In particular we calculated the mean of all the ten handsets and all the handling in free space, then the mean of all the handsets when the user is interacting with one hand, the mean of all the handsets when the user is interacting with two hands and finally the mean of all the handsets for the Specific Anthropomorphic Mannequin(SAM) and hand phantom measurements. For the free space the mean envelope correlation is 0.4 whereas for the cases with the real user and the SAM the mean envelope correlation is 0.3. Hence this random handset has values below the threshold and close to each other in different situations.

Now all the handsets will be analyzed one by one. The next figure shows an overview of the envelope correlation for all the considered handsets for each handset mode in free space or in presence of the user. In the latter case the mean value is computed considering all the users involved in the measurements for each handling and for both frequency bands. The markers represent the mean envelope correlation in low band for each handset and for each way of handling it. On the figure is also plotted the standard deviation for all the handsets in each handset mode to see the variations of the envelope correlation around the mean when the handset mode is changed. Only the low band is considered for all the next analysis on the correlation since in the high band the envelope correlation is constant around 0.1 for each handset and use case

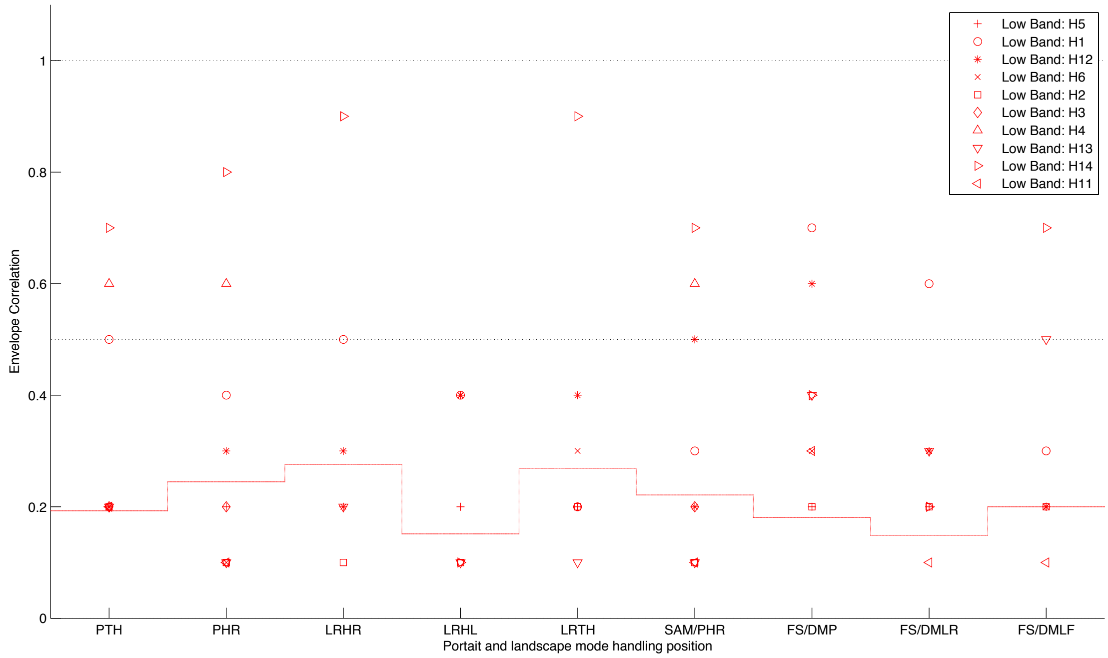


Figure 5.1: Overview of the mean envelope correlation for all the handsets

The table presents a summary of what is shown in the plot .

Use Case	Handset Mode	Mean Envelope Correlation									
		H12	H11	H1	H14	H4	H3	H5	H13	H2	H6
Free Space	DMP	**0.6**	0.3	**0.7**	0.4	**0.8**	0.4	0.2	0.4	0.2	0.3
	DMLR	0.3	0.1	**0.6**	0.2	**0.7**	0.2	0.2	0.3	0.2	0.3
	DMFL	0.2	0.1	0.3	**0.7**	**0.6**	0.2	0.2	0.5	0.2	0.2
Users	PHR	0.3	0.1	0.4	**0.8**	**0.6**	0.2	0.2	0.1	0.1	0.1
	PTH	0.2	0.2	0.5	**0.7**	**0.6**	0.2	0.2	0.2	0.2	0.2
	LRHR	0.3	N/A	0.5	**0.9**	N/A	N/A	0.2	0.2	0.1	0.2
	LRHL	0.4	N/A	0.4	0.1	N/A	N/A	0.2	0.1	0.1	0.4
	av. of LRHR and LRHL	0.4	N/A	0.5	0.5	N/A	N/A	0.2	0.2	0.1	0.3
	LRTH	0.4	N/A	0.2	**0.9**	N/A	N/A	0.2	0.1	0.2	0.3
	SAM and hand phantom	0.5	0.1	0.3	**0.7**	**0.6**	0.2	0.1	0.1	0.1	0.2

Table 5.2: Comparison of mean envelope correlation for different handsets and use case

The values which are above the threshold are highlighted in red. H12 and H1 in free space experience a correlation higher than 0.5, H4 overcomes the threshold either in free space either

with the user whereas H14 has a really high correlation in presence of the user. Therefore apart H14, H4 and in free space H1, all the other handsets perform good from a MIMO performance point of view because low correlation implies high diversity gain. A relevant thing to observe is that H14 is the only handset in which the tilt has a big impact. Indeed the difference between LRHR or Landscape mode Right tilt Two hands(LRTH) and Landscape mode Right tilt Left hand only(LRHL) is 0.8. However this really low correlation in LRHL is confirmed in free space where in DMLR we observe the correlation is close to the LRHL value, i.e. the user does not influence the landscape mode if he interacts with the left hand because in this case he is not touching the two top antennas of the handset. We also computed the mean of LRHR and LRHL value to see if it really fits with the LRTH case. In general the values are close but for H1 and H14 a difference of 0.3 and 0.4 respectively has been observed.
For some handsets, H2 and H5, the user does not entail any variation. For all the other handsets the user decreases the correlation in portrait mode whereas it slightly increases the correlation in landscape. The only exception is H14 where the user increases the correlation in portrait and landscape. H14 has smaller size, two low top band antennas. As we will explain in the next section these are all characteristics leading to high correlation. It is likely the user touching the zone where the antennas are located with one or two hands implies this increase in correlation. The most significant variations between free space and user case have been observed for H12, H1, H14 in portrait mode and H14 in landscape mode.

The SAM and hand phantom measurements correspond to a portrait mode right hand including also part of the body and the head. The same handling for the real user is the PHR thus it is possible to compare them. Looking to the handsets one by one no significant variations have been noticed. The maximum difference is 0.2 for H12. We also compared the mean of the SAM and hand phantom values for all the handsets with the mean of all the cases in which the real user is touching the handset with one hand in order to see if it is possible to approximate the real user with a model of it. The values are identical thus this approximation is acceptable in our study. Moreover comparing the handsets in terms of SAM and hand phantom correlation measurements a big difference has been observed between H11 and H4 or H14 but also between H12 and H2, H5 or H13.

5.1.2 How much do antenna design parameters influence the correlation?

This section presents a study on the impact of the antenna design parameters on the correlation. Focus will be on antenna location, antenna type, resonant frequency, Q-factor, antenna form factor.

Impact of antenna type and locations on the handset on the correlation

As stated in table 3.1 the ten handsets have different characteristics and analyzing them we will be able to see the impact of the design on the correlation. The idea is to compare handsets which have different antennas designs but located in the same place. After having seen the impact of the antenna type we will consider the comparison between handsets with same antennas but located in different places in order to see how the antenna location can affects the correlation. Let's start by comparing H12 and H1. These two handset have different type of antennas located in the same place on the handset. In free space the envelope correlation is similar in portrait while in

landscape is 0.3 higher for H1. By adding the users the correlation decreases for both. Although all the values are below 0.5, H1 has a correlation higher up to 0.3 in Portrait Mode Two hands(PTH) and 0.2 in landscape. Hence it seems that for these two handsets the antenna type has an impact, although small, either in free space either in presence of the users. It is also true the two handsets have different size thus it might be also this one a reason for the variation in correlation. However the influence of the form factor will be studied later in the report.
H11 has the same characteristics of H12 but bigger size. In this case the variation between H11 and H1 is more visible especially in free space. Indeed H1 has an envelope correlation of 0.4 higher in DMP and 0.5 in DMLR. Moreover for H1 the values overcome the threshold thus it reaches the limit for a good MIMO performance. Considering the presence of the user there is a difference of 0.3 for both the portrait modes. It is not possible to compare these handsets in landscape mode when the users are considered since H11 has no measurements available in landscape. Thus it is likely that the antenna type has a big impact on the correlation, especially in free space.
Comparing H12 with H3 and H11 with H3 we see that for both the comparisons the values are similar. This means that in this case the difference either in antenna type(PIFA and single feed MAC) either in antenna location(top/bottom and top right long side/bottom right long side) does not affect the correlation.
Concerning handsets with same antenna type set in different position(H5 and H2) no variations have been observed. Furthermore both handsets have two dual band antennas and BFF. Then the only difference is in the antenna location on the handset and it does not lead to change in correlation.
Looking at the table 5.2 we notice other relevant differences between H11/H12 and H4 or H14. In particular H14 has a much higher correlation in presence of the user respect to H11 and H12. It is up to 0.6 for landscape modes and 0.7 for portrait modes. This gap could be explained by the fact that H14 has two low band antennas at the top. The correlation is expected to be high due to antennas proximity. H4 has a correlation higher up to 0.4 in free space and 0.3 in user case respect to H12. Compared to H11 it has a correlation higher up to 0.6 in free space and 0.3 in user case. Probably the difference between H4 and H11 or H12 is due to the antenna type.

Focusing more on the antennas location the handset have been clustered according to the position of the antennas on them. In particular three groups are considered: handsets with top and bottom antennas (H1, H11 and H12), handsets with top and bottom antennas along the side (H2, H3 and H13) and handsets with two top antennas(H4, H5, H6, H14). Then a mean correlation for each group is computed considering always both use case and all the handset modes.

Use Case	Handset Mode	Mean Envelope Correlation		
		Antenna Location		
		Top and bottom	Two top	Top and bottom on the side
Free Space	DMP	0.5	0.4	0.3
	DMLR	0.3	0.3	0.2
	DMFL	0.2	0.4	0.3
Users	PHR	0.3	0.4	0.1
	PTH	0.3	0.4	0.2
	LRHR	0.4	0.4	0.1
	LRHL	0.4	0.2	0.1
	LRTH	0.3	0.5	0.1
	SAM and hand phantom	0.3	0.4	0.1

Table 5.3: Impact of the antenna location on the correlation

Although the values are low and below 0.5, a general behavior seems to be that the handsets with antennas placed at top and bottom on the long side have a much lower correlation, in particular in presence of the user. As expected handsets with two top antennas are more correlated due to the short distance between the antennas. Hence for an antenna designer a good choice would be having a top long side antenna and a bottom long side one.

What is the influence of the Q?

H11 and H12 have a quality factor equal to 200 and 80 respectively. All the other eight handsets have a much lower Q. Next table shows the mean envelope correlation for H11, H12 and the mean of all the other handsets with low Q. In this way it is possible to compare high and low Q handsets and observe the impact of the quality factor on the correlation.

Use Case	Handset Mode	Mean Envelope Correlation		
		H12	H11	Low Q Handsets
Free Space	DMP	0.6	0.3	0.4
	DMLR	0.3	0.1	0.3
	DMFL	0.2	0.1	0.4
Users	PHR	0.3	0.1	0.3
	PTH	0.2	0.2	0.3
	LRHR	0.3	N/A	0.3
	LRHL	0.4	N/A	0.2
	LRTH	0.4	N/A	0.3
	SAM and hand phantom	0.5	0.1	0.3

Table 5.4: Impact of the Q on the envelope correlation

The results in the table show the Q has not big impact on the correlation for H12 since its values are close to the ones of low Q handsets. On the contrary H11, which has a really high Q, presents a big difference in the general behavior compared to the low Q handsets and H12. The correlation is much lower and this leads to state that it is good to design handsets with very high

Q, i.e. narrowband handsets. H11 has 4 MHz bandwidth and it is enough for a tunable antenna since only one channel has to be covered. High Q implies the efficiency is getting worse [21] hence having low correlation handset as H11 costs in terms of Q.

How much do antenna form factor and resonant frequency affect the correlation?

Next table shows the influence of antenna form factor and resonant frequency on the correlation. Concerning the antenna form factor the handsets are divided in two groups: H12 and H14 in SFF whereas all the others in BFF. Then to obtain the value we simply compute the mean of the correlation values of the handsets that constitute that group.
For the resonant frequency the handsets are clustered in three groups: handsets with two dual band antennas(H1, H2, H5, H6, H11, H12), handsets with two low band antennas(H13, H14), handsets with a dual band and a high band antenna(H3, H4). The values in the table are obtained by computing the mean of the correlation values of the handsets that constitute the considered group.

Use Case	Handset Mode	Form Factor		Resonant Frequency		
		SFF	BFF	2 dual band antennas	2 low band antennas	1 dual band antenna 1 high band antenna
Free Space	DMP	0.5	0.4	0.4	0.4	0.6
	DMLR	0.3	0.3	0.3	0.3	0.5
	DMFL	0.5	0.3	0.2	0.6	0.4
Users	PHR	0.6	0.2	0.2	0.5	0.4
	PTH	0.5	0.3	0.3	0.5	0.4
	LRHR	0.6	0.2	0.3	0.6	N/A
	LRHL	0.2	0.2	0.3	0.1	N/A
	LRTH	0.7	0.2	0.3	0.5	N/A
	SAM and hand phantom	0.6	0.2	0.2	0.4	0.4

Table 5.5: Impact of the antenna form factor and resonant frequency on the envelope correlation

Let's analyze first the influence of the antenna form factor. It is obvious that the form factor has a big impact since a big difference is noted, especially in presence of the user. The handsets with smaller size have a much higher correlation. This is due to the distance in terms of λ between the antennas. A smaller size means shorter distance and thereby the antennas are more correlated. Even if SFF handsets and BFF handsets present these variations in correlation we know that for H11(BFF) and for H12(SFF) the mutual coupling between the antennas is the same, i.e. -9dB.
Regarding the resonant frequency, although the values are close to each others, the handsets with two low band antennas and the handsets with a dual and a high band antenna have a correlation slightly higher than the handsets with two dual band antennas either in free space either in user case. In particular the handsets with two low band antennas present the highest correlation, especially in presence of the user. One reason could be the antenna location, e.g. for H14 the antennas are placed both at the top. Another reason could be that both the antennas work only in low band.
From the design point of view a handset with small form factor and two low band antennas, i.e. H14, leads to higher correlation thus it is not good. It is much better a handset with big form factor and two dual band antennas like H11, H5 or H2.

5.1.3 Comparison between simulated and measured data

This comparison will concern only handset 11 and 12 since the data from the simulation are available only for these handsets. H11 will be compared only for free space.
In the table below the comparison is listed. For the simulation the three values are referred to the mean envelope correlation of isotropic, Taga and AAU channel model respectively. For the measurements the value is referred to PHR since it is the closest to firm and soft grip case.

<table>
<tr><th rowspan="3">Use Case</th><th rowspan="3">Handset</th><th colspan="4">Mean Envelope Correlation</th></tr>
<tr><th colspan="2">Low Band</th><th colspan="2">High Band</th></tr>
<tr><th>Simulation</th><th>Measurements</th><th>Simulation</th><th>Measurements</th></tr>
<tr><td rowspan="2">Free Space</td><td>H12</td><td>0.5/0.6/0.8</td><td>0.6</td><td>0.1/0/0</td><td>0.1</td></tr>
<tr><td>H11</td><td>0.5/0.6/0.7</td><td>0.3</td><td>0.1/0.1/0.2</td><td>0.1</td></tr>
<tr><td rowspan="2">Users</td><td rowspan="2">H12</td><td>Firm Grip
0.1/0.2/0.4</td><td rowspan="2">0.3</td><td>Firm Grip
0/0/0</td><td rowspan="2">0.1</td></tr>
<tr><td>Soft Grip
0.4/0.6/0.8</td><td>Soft Grip
0/0/0</td></tr>
</table>

Table 5.6: Comparison between simulated and measured data for H11 and H12

Looking at the values in the low band seems that for H12 in free space the Taga model is the one that fits better with the model in the measurements whereas for H11 it is not really possible to state which of the three models is closer to the one considered in the measurements. By considering the users for H12, the measured envelope correlation is closer to Taga or AAU for the firm grip and to isotropic model for the soft grip.
In the high band the values are so close that each model could be the one that fits the most with the measurements. This is valid for both handsets and for each use case.
In conclusion we can state that from the available data it is not possible to find which of the channel model considered in the simulation is the closer to the realistic model considered in the measurements.

5.1.4 Which is the best design for the correlation?

From the analysis done it turns out that the best design is the handset eleven. Although in table 5.2 is shown that also other handsets have low correlation, the studies done on the design parameters' impact leads to this conclusion. Indeed H11 respects all the characteristics for a low correlation handset like big form factor, two dual band antennas(one at the top and the other at the bottom), high Q and even with the presence of the user and for the SAM measurements it has a low correlation. It is also true that a handset like H2 or H5 experiences a really low correlation either in FS either in presence of the user even if H5 has two top antennas. These three handsets have some characteristics in common like resonant frequency and form factor but they differ for antenna type, quality factor and antenna location. Probably these two latter have more impact in terms of variation in correlation.
The handsets which experience the worst correlation are H4 and H14. They have two top antennas, both low band for H14 while one is dual band an the other is mono band for H4. Moreover H14 has a small for factor which diminishes the distance between the antennas.

5.2 Branch Power Ratio

In this part we will show and analyze the BPR of different handsets obtained from the measurements campaign. We will present different tables and figures with mean values of the BPR in low and high band for ten handsets. Each of these handsets has specific characteristic such as different antenna location, resonant frequency, High/Low Q and form factor and they are studied in different use case. In fact the variation of the BPR is analyzed for each of these handsets depending on different handling, with or without user, allowing to study the variation of the MEG of each branch. It has been experienced that the user interaction can have a strong impact on the antenna capacity to receive a signal. By studying the variation of the BPR we will then be able to choose which handset is more fitted to optimize the MIMO system according to different use case.

The BPR is the ratio of the MEG of two antennas and we can consider that handset design, handling, user interference and location will have have an impact on the BPR variation. In fact depending on which MIMO diversity combining technique is used the BPR values and its variation is considered as a key factor of the overall efficiency of the system [40]. The antenna diversity techniques considered are antenna combining (AC), maximum ratio combining (MRC) and equal-gain combining (EGC). Basically for AC the receiver selects the antenna with the strongest received signal, for MRC the receiver weighs the received signal according to channel information and sum the phase compensated signal, then for the EGC the received signal is the sum of the phase compensated channel from all the receive antennas with a weight fixed. By selecting the branch with the best SNR the AC technique does not maximize the use of diversity gain. However for such technique a high BPR will allow to maximize the diversity gain of such technique.
By considering these technique similar MEG and small variation should be favorable to MRC and EGC techniques to obtain a high diversity gain [40] [41]. A branch having high noise level will provide more noise to the system when it is combined with a branch having lower noise level [40]. Knowing this we can consider 0 as the best value achieved for the BPR as the two MEGs are similar in this case. Moreover small variation of the BPR according to user interaction will be considered having a better impact on the reliability of the system than big variation which can induce errors of channel estimation for MRC techniques.

Before beginning this part we have computed and analyzed several results coming from the measurement and we have observed that different transmitters have a negligible influence on the variation of the branch power ratio. Therefore we have computed the mean of the values coming from the two transmitters considered.

5.2.1 Handset Results

In the plot 5.2 we can observe the BPR variation of the ten handset in both the frequency bands in function of different use cases. The red markers represent the low band and the blue ones represent the high band. Each marker represents a different handset. We have also added blue and red line respectively high and low band which represent the standard deviation between each handset. The standard deviation shows the BPR variation between each handset and allows to highlight the impact of the handset design on the BPR variation. We can see that the values are pretty high and vary between 2dB and 5.8dB. We can therefore deduce as expected that antenna design characteristics such as antenna location, High/Low Q, resonant frequency and form factor interfere in the variation of the BPR. We notice also that the BPR in high and low band reacts differently for each handset and use case. However the low band seems to be more sensitive to higher BPR variation between handsets for FS and user case. As the attenuation in FS is higher for high band we can deduce that the handset will receive less power. Therefore the MEG variation due to the environment and user interaction will be smaller than the one in the low band. Such observation indicates that the antenna design will have a bigger impact on the BPR variation in the low band.

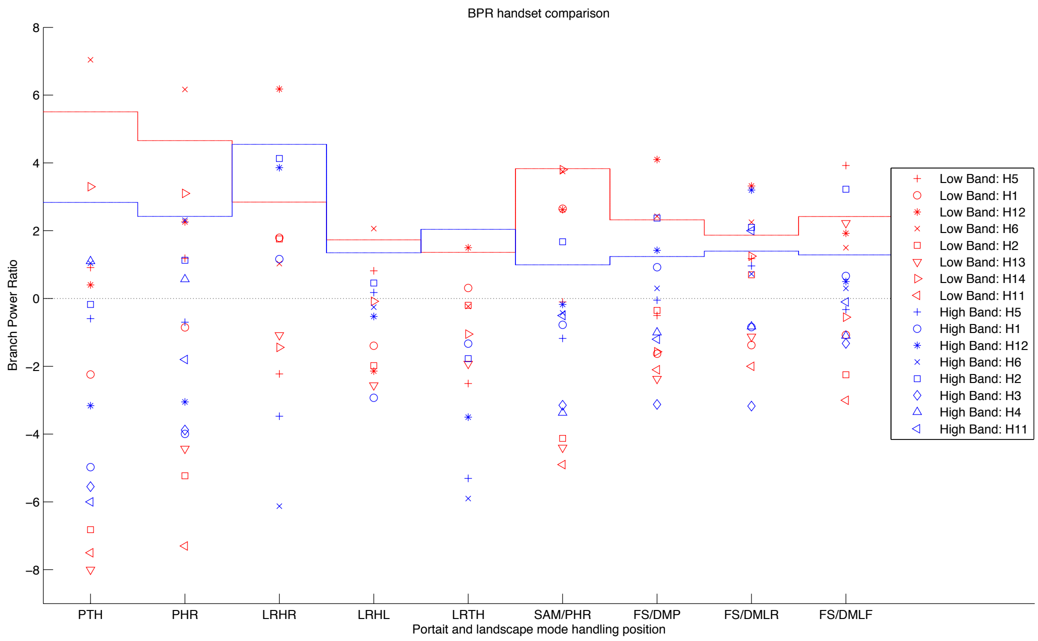


Figure 5.2: BPR of different handset

On the table 5.7 we can see all the BPR values of each handset having a more precise information on the BPR variation.

Computing the mean values of all the handsets we obtained a random design which allows us to see what BPR we can expect. Therefore in FS the BPR value is equal to 2dB in low band and 1dB in high band. With user case the BPR is equal to 3dB in low band and 2dB in high band. No matter the design, low band seems to achieve a higher BPR than high band. Moreover in general the user increases the BPR. Results for PHR case and SAM one are not similar in low band. PHR achieves a BPR of 4dB and the SAM 3dB. In high band the difference is even more important with 3dB for PHR and 1dB for SAM. We can conclude that the SAM configuration is not fitted to the reality for the BPR measurement instead of the correlation where the SAM is closer to the real user.

Use Case	Handset Mode	Frequency	Branch Power Ratio									
			H12	H11	H1	H14	H4	H3	H5	H13	H2	H6
Free Space	DMP	Low Band	4	-2	-2	-2	**30**	**-18**	-1	-2	0	2
		High Band	1	-1	1	N/A	1	-3	0	N/A	2	0
	DMLR	Low Band	3	-2	0	1	**29**	**-16**	1	-1	1	2
		High Band	3	-1	-1	N/A	1	-3	1	N/A	2	1
	DMFL	Low Band	2	-3	-1	-1	**25**	**-14**	4	2	-2	2
		High Band	1	0	1	N/A	-1	-1	0	N/A	3	0
Users	PHR	Low Band	2	-7	-1	3	**29**	**-13**	1	-4	-5	6
		High Band	-3	-2	-4	N/A	1	-6	-1	N/A	1	2
	PTH	Low Band	0	-8	-2	3	**29**	**-15**	1	-8	-7	7
		High Band	-3	-6	-5	N/A	1	-6	-1	N/A	0	1
	LRHR	Low Band	6	N/A	2	-1	N/A	N/A	-2	-1	2	1
		High Band	4	N/A	1	N/A	N/A	N/A	-3	N/A	4	-6
	LRHL	Low Band	-2	N/A	-1	0	N/A	N/A	1	-3	-2	2
		High Band	1	N/A	-3	N/A	N/A	N/A	0	N/A	1	0
	LRTH	Low Band	2	N/A	0	-1	N/A	N/A	-3	-2	0	0
		High Band	-4	N/A	-1	N/A	N/A	N/A	-5	N/A	-2	-6
	SAM and hand phantom	Low Band	3	-5	3	4	**28**	**-14**	0	-4	-4	4
		High Band	0	-1	-1	N/A	-3	-3	-1	N/A	2	0

Table 5.7: Comparison of branch power ratio for different handsets and use case

According to the handset characteristics(table 3.1) and on the way is computed the BPR we can define several groups. Therefore we will use the data contained in this table to compute different groups useful to study the BPR dependence on design parameter.

Resonant frequency of the antenna design

The high BPR positive values for H4 and negative for H3 in low band are explained by these handsets having one antenna working in high band and a second antenna working in both bands. For the handset 4 the antenna 1 which is dual band is located at the top and the antenna 2 on the top right long side. Therefore we can expect that for low band only the antenna 1 will have a high MEG and the antenna 2 a very low MEG. The dual band antenna will be the only antenna able to receive incoming power from the transmitters explaining its high MEG. We can deduced that the ratio of the BPR is the MEG of the antenna 1 over the MEG of the antenna 2 leading to a high BPR. In the same way we can observe this time high negative values for H3 for low band. As for this two handsets low band values are very high and will strongly change the mean values, we will not add them to handsets group. If we were able to expect a variation of the BPR according to which resonant frequency is chosen especially if the two antennas in the handset are mono-band and have different resonant frequencies. However dual-band antennas have the same impact of two low-band antennas on the BPR variation. According to the results if we compare the handset 13 and handset 11 they have the same form factor and antenna location, the variation noticed is too low for making any conclusion. In order to keep a low BPR variation between high and low band handsets with two dual-band antennas are more fitted than handsets with one dual-band and one mono-band antenna.

5.2.2 Impact of the receiver location on the BPR

In this paragraph we are focused on the influence of the location of the handset in the room during the measurement on the BPR. As showed in the figure 3.1 the room is modeled with four main locations A,B,C and D. As we can expect each location will receive different incoming power for each angle of arrival. Therefore the handset will receive more or less incident power and we can predict an influence of the location on the BPR.
In the next plot we have computed for the handset H1 the BPR variation depending on the locations in the room and on the handling positions. In this plot the circle represents low band and the cross high band, each location is represented by different colors. We have also added to the plot a blue line for low band and a red one for high frequency representing the standard deviations of the BPR at different locations. We can first notice that the standard deviation is not equal to zero. It is varying between 2.5dB and 0.1dB depending on the use case and the frequency. The measurement location on the room has therefore a noticeable impact on the variation of the BPR. Moreover the user has also an impact on the variation of the standard deviation of the BPR at different location. This observation is expected since the user or the handset handling have an impact on the BPR modifying the incident power received. According to the results we cannot notice a stronger variation in low or high band. The user does not seem to have a big impact on the standard deviation in comparison with the free space. We can notice that for example in free space and DMP case the BPR is positive for three locations except for the location B where is negative meaning that at this location the MEG of the bottom antenna becomes lower than the top's one. We can observe this change on several use cases allowing to suggest some LOS or NLOS case depending on the environment and user interaction which impact the total incident power at the antenna receiver.

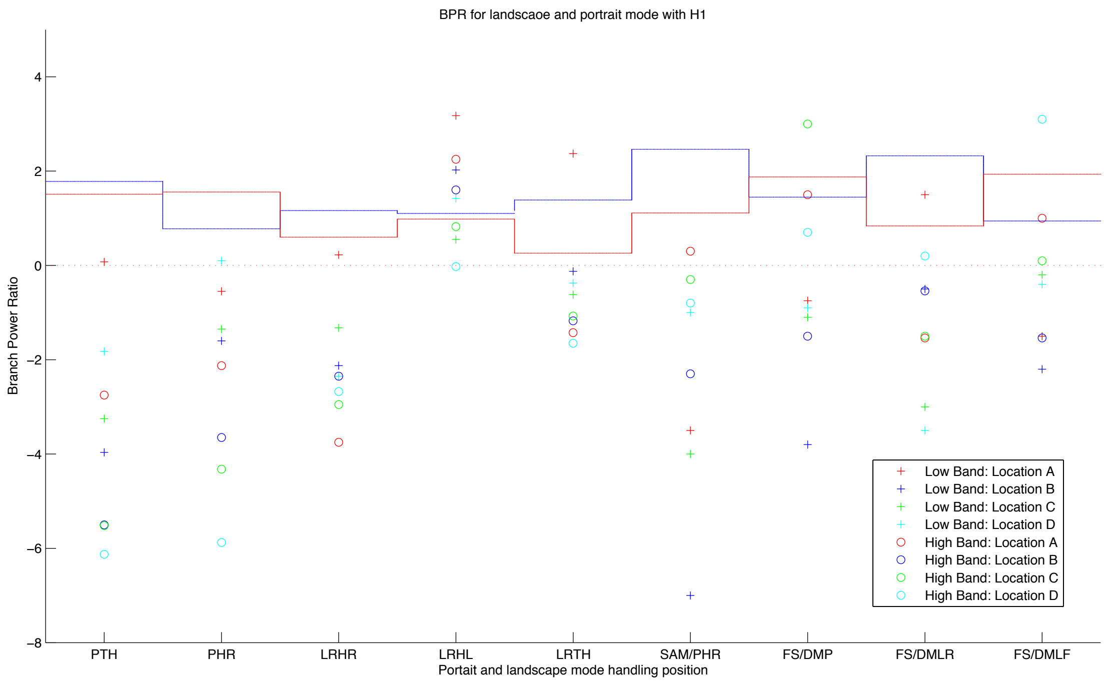


Figure 5.3: BPR of H1 with different location with users or in free space

Impact of the receiver location on the BPR for different handset design

In the table below we have computed the BPR for three handsets having different Q and the standard deviation of the BPR. The different locations in the room are still considered. The results for the standard deviation is separated by the slash / respectively for H1, H11 and H12.
The BPR of H11 and H12 which have the highest Q seems to be less sensitive to location variation in free space. Even adding the users interaction H11 is again less sensitive to location variation in comparison with H12 and H1. From the results the strongest Q-factor seems to have the lowest BPR variation due to different locations in the room.
By computing the standard deviation between different locations we can observe that statically the location B seems to performs a highest standard deviation than the other locations. We can therefore expect on this location important BPR change.

Side	Use Case	Branch Power Ratio			Standard Deviation			
		H1	H11	H12	A	B	C	D
A	Free Space	-1	-2	4	0/0/0	2/1/0	0/0/0	0/ 0/ 0
	Users	2	-9	5	0/0/0	4/2/0	3/0/1	1/1/3
B	Free Space	-4	-3	4	2/0/0	0/0/0	2/1/0	2/0/0
	Users	-4	-11	4	4/2/0	0/0/0	1/1/1	3/0/3
C	Free Space	-1	-2	5	0/0/0	2/1/0	0/0/0	0/0/0
	Users	-3	-9	3	3/0/1	1/1/1	0/0/0	2/1/2
D	Free Space	-1	-2	4	0/0/0	2/0/0	0/0/0	0/0/0
	Users	0	-11	0	1/1/3	3/0/3	2/1/2	0/0/0

Table 5.8: Branch Power Ratio for three handsets in portrait mode with low frequency

5.2.3 Antenna location impact on the BPR

In this part the handsets are divided by their antenna location on the them. The aim is to study handset design influence on the variation of the BPR and to determine which antenna location is the best to obtain a low BPR value and small variations.
We can define four handsets groups according to the antenna location without considering left or right side location of some handset. BPR computation for H4, H5 and H14 is a ratio between two top antennas, for H13, H12, H11, H2 and H3 it is a ratio of bottom over top antennas, for H6 is a side over top antenna location ratio and finally for H1 is a top over bottom antenna.

We computed the average BPR of different handsets for each of these groups in low and high band (Table 5.9). As expected we can observe strong differences between the different groups. When we look at the Bottom/Top handset we can observe a low BPR in free space. That's means that the two MEG are close in FS for antennas located at the top and at the bottom. When we observe Top/Top and Side/Top results in free space and compare them with top and bottom antennas results, the absolute values seems to be higher in general. The distance between antennas and their positions can therefore have an impact on the differences observed.
Furthermore we can observe that the BPR's variation of handsets with top and bottom antennas are more sensitive to user interaction. This result was expected as the two antennas are located at different positions and the user has more chances to interact with only one antenna. By interacting only with one antenna the user increases the absolute value of the BPR as the ratio, except for H1, is in this case bottom over top antenna. When the user is interacting with one antenna he seems to

decrease the MEG of this one. In fact for PHR and PTH mode where the user is only touching the bottom antenna we can observe a strong decrease of the absolute value of the BPR and therefore a decrease of the MEG of the bottom antenna involving negative values. When the handset is rotated on the right side for landscape mode the user in only interacting with the top antenna and this time the BPR is positive for low and high band meaning a decrease of the MEG of the top antenna. We notice the same conclusion for Top/Bottom case. However for handsets with two top antennas the user interacts with them only in LRHR and LRTH. For these two cases we observe a strong variation of the BPR which becomes negative involving that even with antennas located closely the hand interacts differently with each antennas. The Side/Top case is similar to the bottom and top antenna case in terms of user sensitivity as we observed also some strong variation of the BPR in portrait mode.

Use Case	Handset Mode	Frequency	Branch Power Ratio			
			Antenna Location			
			Bottom/Top	Top/Top	Top/Bottom	Side/Top
Free Space	DMP	Low Band	0	-2	2	-2
		High Band	0	1	0	1
	DMLR	Low Band	0	1	2	0
		High Band	0	1	1	-1
	DMFL	Low Band	0	2	2	-1
		High Band	1	-1	0	1
Users	PHR	Low Band	-4	2	6	-1
		High Band	-3	0	2	-4
	PTH	Low Band	-6	2	7	-2
		High Band	-4	0	1	-5
	LRHR	High Band	2	-2	1	2
		High Band	4	-3	-6	1
	LRHL	Low Band	-2	1	2	-1
		High Band	1	0	0	-3
	LRTH	Low Band	0	-2	0	0
		High Band	-3	-5	-6	-1
	SAM and hand phantom	Low Band	-3	2	4	3
		High Band	-1	-2	0	-1

Table 5.9: Impact of the antenna location on the Branch Power Ratio

In the previous plot (Fig. 5.3) we have a confirmation of this observation. In fact for PTH, PHR, LRHR and LRTH where we have a direct hand interaction with the top antenna the BPR is always negative. When this time the hand is interacting with the bottom antenna we have only positive values.
Handsets with top and bottom antenna have a BPR closer to 0 in free space in comparison with the other designs. This aspect is important and allows to obtain a higher diversity gain by using techniques such as MRC or EGC. However these handsets are more sensitive to BPR variation with an user as in most of the case he is directly interacting with one antenna. These changes decrease the reliability of the design in comparison of the FS case. Therefore with an user interaction handsets with two top antennas are more effective to reduce BPR variation.

5.2.4 What is the influence of the Q and the Form Factor?

As explained in the correlation part H11 and H12 have a quality factor equal to 200 and 80 respectively. All the other eight handsets have a much lower Q. Moreover handset H12 and H14 have a small form factor (Bar type 100x40) and all the other handset have a big form factor (PDA type 111x59). In the next table we will show the mean BPR for H11, H12 and the mean of all the other handsets with low Q. In the same way we will do it also for the two form factors. We will investigate the impact of this two parameters on the BPR.
The antenna design study on H11 and H12 [21] shows that the S-parameters of antenna 1 S_{11} and antenna 2 S_{22} are not equal in low band for H11. We observe $12dB$ difference between the two S-parameters which implies more power reflected for the second antenna than for the first one. For handset 12 we don't observe in low band such difference in the S-parameters. Therefore looking the BPR results in free space we can see that the H11 has only negative values meaning that the antenna 1 has a higher MEG than antenna 2 which is coherent with S-parameters values. In parallel H12 has only positive values in free space which implies that the design of this handset combined with an equal S-parameters promotes the power received at the bottom antenna.

According to the results (Table: 5.10) a high Q can imply higher negative or positive BPR values than low Q handset which is more close to a 0 value. Moreover when we add the user interference the highest Q handset experiences the strongest BPR variation. Therefore high Q handset seems to be more sensible to the user interference.

When we look to form factor aspect of the handsets (Table 5.10) the SFF seems to have values closer to 0 than BFF. We can also notice that SFF is less sensible to user interaction.

Use Case	Handset Mode	Frequency	Branch Power Ratio				
			H12	H11	Low Q Handsets	BFF Handsets	SFF Handsets
Free Space	DMP	Low band	4	-2	-1	1	-1
		High band	1	-1	0	1	0
	DMLR	Low band	3	-2	1	2	0
		High band	3	-1	0	3	0
	DMFL	Low band	2	-3	1	1	0
		High band	1	0	0	1	1
Users	PHR	Low band	2	-7	0	3	-2
		High band	-3	-2	-1	-3	-1
	PTH	Low band	0	-8	-1	2	-3
		High band	-3	-6	-2	-3	-2
	LRHR	Low band	6	N/A	0	2	0
		High band	4	N/A	-1	4	-1
	LRHL	Low band	-2	N/A	-1	-1	-1
		High band	-1	N/A	-1	-1	-1
	LRTH	Low band	2	N/A	-1	0	-1
		High band	-4	N/A	-4	-4	-4
	SAM and hand phantom	Low band	3	-5	0	3	-1
		High band	0	-1	-1	0	-1

Table 5.10: Impact of the Q and of the form factor on the Branch Power Ratio

5.3 Received power

This section presents the analysis of the measured received power.

5.3.1 Analysis of the results

The received power for each handsets is analyzed in order to compare all the handsets and highlight relevant differences.
As for the other parameters we first look at the influence of the location in the room in which the measurement has been realized. Looking at the data, changing the location leads to a maximum variation of $3dB$ in the received power and this is valid for all the handsets. Thus for simplicity we will not consider all the locations in the room but we will compute the mean of all the measurements in the four locations.

Frequency dependence and influence of the user

In the next tables(one for low band and one for high band) the mean values of the received power are listed for each handset in all the handset modes. Focus is given to the antenna location to see if one of the two antennas receives more power and the difference between free space and user case. Antenna1 and antenna2 are referred to table 3.1.

Use Case	Handset Mode	Antenna Number	Received Power [dBm]									
			H12	H11	H1	H13	H4	H3	H5	H14	H2	H6
Free Space	DMP	1	-118	-112	-110	-113	**-138**	-109	-111	-111	-111	-111
		2	-114	-114	-112	-116	N/A	N/A	-111	-113	-111	-108
	DMLR	1	-119	-114	-114	-115	**-139**	-112	-111	-114	-112	-111
		2	-118	-116	-115	-118	N/A	N/A	-110	-112	-112	-111
	DMFL	1	-120	-113	-115	-122	**-140**	-114	-115	-118	-112	-114
		2	-119	-115	-116	-123	N/A	N/A	-113	-119	-115	-113
Users	PHR	1	-123	-111	-113	-115	**-141**	-115	-114	-120	-113	-118
		2	-121	-119	-115	-120	N/A	N/A	-112	-117	-119	-111
	PTH	1	-112	-115	-113	-115	**-142**	-115	-115	-122	-113	-120
		2	-122	-123	-115	-112	-N/A	N/A	-112	-124	-120	-112
	LRHR	1	-122	N/A	-115	-118	N/A	N/A	-113	-118	-116	-115
		2	-117	N/A	-114	-119	N/A	N/A	-115	-120	-114	-114
	LRHL	1	-117	N/A	-112	-116	N/A	N/A	-113	-115	-114	-112
		2	-119	N/A	-115	-119	N/A	N/A	-112	-114	-115	-112
	av. of LRHR and LRHL	1	-120	N/A	-114	-117	N/A	N/A	-113	-117	-115	-114
		2	-118	N/A	-115	-119	N/A	N/A	-114	-117	-115	-113
	LRTH	1	-121	N/A	-118	-118	N/A	N/A	-116	-119	-116	-114
		2	-120	N/A	-116	-119	N/A	N/A	-119	-120	-115	-114
	SAM and hand phantom	1	-122	-113	-113	-115	**-141**	-113	-113	-120	-113	-116
		2	-121	-118	-118	-120	N/A	N/A	-113	-119	-117	-112

Table 5.11: Mean received power for all the handsets in low band

The plot 5.4 shows the behavior of the power received by the two antennas of each handset in the low band. Red markers are for antenna 1 and blue ones for antenna 2.

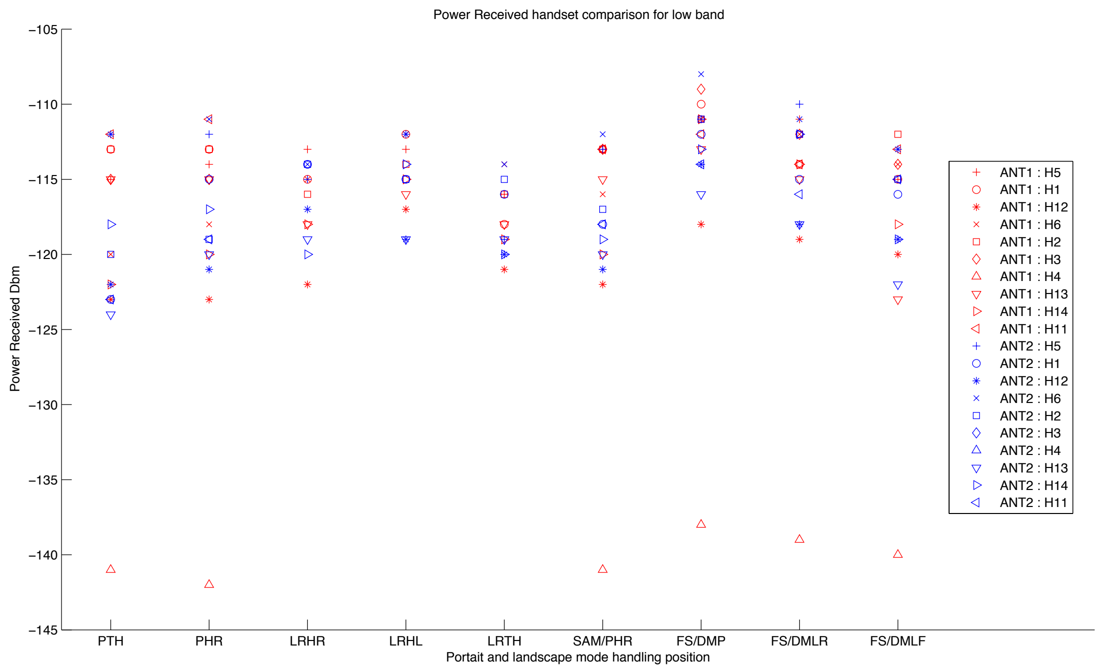


Figure 5.4: Power received by the two antennas for all the handsets in low band

Use Case	Handset Mode	Antenna Number	Received Power [dBm]							
			H12	H11	H1	H4	H3	H5	H2	H6
Free Space	DMP	1	-122	-121	-122	-120	-122	-120	-123	-120
		2	-121	-122	-121	-122	-125	-120	-121	-120
	DMLR	1	-124	-122	-123	-121	-120	-120	-123	-119
		2	-120	-120	-123	-121	-123	-119	-120	-119
	DMFL	1	-125	-123	-124	-123	-123	-123	-125	-123
		2	-124	-124	-123	-124	-125	-123	-123	-122
Users	PHR	1	-127	-123	-125	-125	-124	-123	-128	-125
		2	-131	-125	-129	-125	-128	-124	-126	-123
	PTH	1	-127	-124	-125	-126	-124	-123	-128	-126
		2	-131	-131	-130	-125	-130	-124	-129	-124
	LRHR	1	-126	N/A	-127	N/A	N/A	-122	-128	-122
		2	-123	N/A	-126	N/A	N/A	-126	-123	-128
	LRHL	1	-125	N/A	-125	N/A	N/A	-122	-126	-122
		2	-125	N/A	-128	N/A	N/A	-122	-125	-122
	av. of LRHR and LRHL	1	-126	N/A	-126	N/A	N/A	-122	-127	-122
		2	-124	N/A	-127	N/A	N/A	-124	-124	-125
	LRTH	1	-127	N/A	-127	N/A	N/A	-123	-127	-122
		2	-130	N/A	-129	N/A	N/A	-127	-125	-128
	SAM and hand phantom	1	-123	-122	-124	-122	-122	-121	-125	-122
		2	-127	-127	-125	-123	-125	-122	-123	-121

Table 5.12: Mean received power for all the handsets in high band

As expected all the handsets receive less power in the high band than in the low band. In the low band the wave travels more in terms of λ due to the lower frequency thereby the power is less attenuated. On the contrary H4 receives less power in the low band(highlighted in red). The difference between low and high band is up to $18dB$ for this handset. Moreover comparing H4 with the other handsets a big variation in the low band has been noticed whereas in the high band the values are included in few dBs. Indeed either in free space either considering the user H4 receives between 18 and 30 dB less in the low band respect to the other handsets.
For the SAM and hand phantom measurements the variation between low and high band is between 4 and 10 dB for all the handsets except H4 in which is about 20dB.

The values in tables 5.11 and 5.12 also highlighted by figure 5.4 confirm that the presence of the user decreases the received power because of the absorption losses and also shadowing if considering SAM and hand phantom measurements. In the low band and portrait mode the user adds between 5 and 7 dB for H12, H3 and H6, between 3 and 4 dB for H1, H5 and H4, 2 or 3 dB for H2 and H13 whereas around 10dB for H14. In high band the user adds 5dB for H12 and H2, between 2 and 4 dB for all the others. Concerning the landscape mode the user experiences maximum 5dB more in the low band and between 2 and 4 dB in high band.
The tables also show that for each handset the power received from the two antennas is similar. Differences up to 10dB have been observed in PHR and PTH for H2, H6, H11 and H12 in low band. In high band 6-7dB of variation has been noticed in PTH for H11 and H3. In portrait the user is interacting with the bottom antenna and this is why the bottom antenna receives less power. In general there are small differences but not significant to be considered in terms of design. This means that, looking at the handset one by one, the antenna location on the handset does not have big influence. It is a confirmation of what has been found in the simulation for H11 and H12. Hence this allow us to be sure about the good modeling done in the measurements in terms of received power.

What is the impact of the quality factor and resonant frequency?

For the quality factor study the handsets are divided in three categories. H11 has $Q = 200$, H12 has $Q = 80$ [21] and all the others have low Q. Hence we are considering the two high Q handsets comparing them with the mean of all the values relative to the handsets with low Q.
Regarding the study on the resonant frequency, like in the correlation, the handsets are clustered in three groups: handsets with two dual band antennas, handsets with two low band antennas and handsets with a dual band antenna and a high band antenna.

Use Case	Handset Mode	Frequency Band	Quality Factor			Resonant Frequency		
			H12	H11	Low Q handsets	2 dual band antennas	2 low band antennas	1 dual band antenna 1 high band antenna
Free Space	DMP	Low Band	-116	-113	-113	-112	-113	-124
		High Band	-122	-122	-121	-121	N/A	-122
	DMLR	Low Band	-119	-115	-115	-114	-121	-126
		High Band	-122	-121	-121	-121	NA	-121
	DMFL	Low Band	-120	-114	-118	-115	-122	-127
		High Band	-125	-124	-123	-124	N/A	-124
Users	PHR	Low Band	-122	-115	-117	-116	-118	-128
		High Band	-129	-124	-125	-126	N/A	-125
	PTH	Low Band	-117	-119	-118	-116	-118	-129
		High Band	-129	-128	-126	-127	N/A	-126
	LRHR	Low Band	-120	N/A	-116	-119	-118	N/A
		High Band	-125	N/A	-125	-125	N/A	N/A
	LRHL	Low Band	-118	N/A	-114	-114	-116	N/A
		High Band	-125	N/A	-124	-124	N/A	N/A
	LRTH	Low Band	-121	N/A	-117	-117	-119	N/A
		High Band	-129	N/A	-126	-127	N/A	N/A
	SAM and hand phantom	Low Band	-122	-116	-117	-116	-119	-127
		High Band	-125	-125	-123	-124	N/A	-123

Table 5.13: Impact of the quality factor and resonant frequency on the power received

The analysis on the Q-factor shows that in general H11 and the handsets with low Q receive more power in free space and also considering the user. Indeed there are not significant variations between them. H12 which has a high Q but lower than H11 receives less power even than the low Q handsets. These results lead to the conclusion that handsets with high Q and others with much lower Q have the same performance in terms of power received.
The table also shows that handsets with two dual band antennas receive more power even though the difference with handsets with two low band antennas is small. On the contrary the handsets with a dual band antenna and a high band antenna receive much less power, especially in free space if compared with the other two groups.
As summary of this study on Q-factor and resonant frequency we can state that H11 has a good design to receive more power.

Influence of antenna form factor and antenna location

With this type of analysis we want to investigate if the antenna form factor and the location of the antennas on the handset can have an influence on the received power. The groups in which the handsets are divided are the same considered for the correlation.

Use Case	Handset Mode	Frequency Band	Form Factor		Antenna Location		
			SFF	BFF	Top and bottom on the short side	Two top	top and bottom on the long side
Free Space	DMP	Low Band	-114	-113	-113	-112	-115
		High Band	-122	-121	-122	-123	-120
	DMLR	Low Band	-116	-115	-116	-114	-115
		High Band	-122	-121	-122	-122	-120
	DMFL	Low Band	-119	-117	-116	-117	-119
		High Band	-125	-123	-124	-124	-123
Users	PHR	Low Band	-120	-117	-117	-116	-119
		High Band	-129	-125	-127	-127	-124
	PTH	Low Band	-120	-117	-116	-115	-121
		High Band	-129	-126	-128	-128	-125
	LRHR	Low Band	-119	-115	-117	-117	-116
		High Band	-125	-125	-125	-126	-125
	LRHL	Low Band	-116	-114	-116	-116	-113
		High Band	-125	-124	-126	-126	-122
	LRTH	Low Band	-120	-117	-119	-117	-117
		High Band	-129	-126	-128	-126	-125
	SAM and hand phantom	Low Band	-121	-117	-118	-116	-119
		High Band	-125	-123	-125	-124	-122

Table 5.14: Influence of antenna form factor and antenna location on the power received

Focusing on the form factor differences has been noticed in free space and considering the user which allow us to state that BFF handsets receive more power. This is valid for each handset mode in both frequency bands.
Regarding antenna location it turns out that in free space any relevant variations is observed. By adding the user the handsets with two top antennas receive slightly more power in portrait mode. When the antennas are both at the top and the handset is in portrait mode, the user is slightly interacting with the sources therefore less incoming power is blocked by his interaction. This is coherent with theoretical knowledge. Indeed low values of BL, i.e. higher received power, are expected when the antennas are placed at the top [28]. For the same reason when the user holds the mobile in landscape mode, the handsets with top an bottom on the long side receive more power.

5.3.2 Which handset performs better?

This analysis allows to state that more than one handset has a good antenna design in terms of power received. Instead the worst handset is doubtless H4 which has really low signal strength in reception in low band. H11, H13, H2, H1 or H5 present characteristics leading to receive more power. For H1 and H5 the user interaction does not have big impact on them. H13 presents two low band antennas which could be a disadvantage in terms of size in wavelength of the antennas while H11 has a really high Q.
Hence apart H4 each handset present a good design to have a received signal with a good level of strength. Our conclusion is that H2, H11 and H5 are the ones which perform better in each analysis done on the power received.

5.4 Capacity

5.4.1 Results

In this part we will analyze capacity results coming from different handsets studied so far. Then in a second part we will compare capacity results to the envelope correlation and BPR coming from the different parts in order to highlight their influence on the channel capacity defined in the chapter 2.

We are here focused on a MIMO system with two transmitters and two receivers with mean capacity results mainly varying between 4.5 $[Bps/Hz]$ and 5.7 $[Bps/Hz]$. In comparison mean capacity results achieved with SISO systems and SIMO with two receivers are varying between 2.5$[BpsHz/]$ and 3.5 $[Bps/Hz]$ depending of different handsets and use cases. By looking at the theoretical capacity equations (eq: 2.30, 2.32 and 2.34) such difference is coherent with a difference in terms of capacity between MIMO and SIMO/SISO close to time $N = 2$ the number of receiver. By not including handset 3 and 4 which can be considered as SIMO system in low band the mean capacity achieved with all the handset in low band for FS is 5.3 $[Bps/Hz]$ and 5.5 $[Bps/Hz]$ in high band. With an user interaction the mean capacity for all the handset is then 5.4 $[Bps/Hz]$ in low and 5.5 $[Bps/Hz]$ in high band. Capacity variations are low and therefore seems not to be too impacted by the user interferences moreover the high band seems to perform higher capacity in general. We can also notice that the PHR case and the SAM one achieved the same capacity in low and high band with 5.4 and 5.5 $[Bps/Hz]$ which confirm the efficiency of the SAM model.

Use Case	Handset Mode	Frequency	Capacity $[BpsHz/]$									
			H1	H2	H3	H4	H5	H6	H13	H14	H11	H12
Free Space	DMP	Low Band	4.7	5.4	2.9	2.9	N/A	5.3	5.2	5.3	5.4	N/A
		High Band	5.5	5.5	5.5	5.4	N/A	5.6	N/A	N/A	5.6	N/A
	DMLR	Low Band	5.1	5.5	2.9	3.0	5.6	5.4	5.3	5.4	5.6	5.4
		High Band	5.5	5.6	5.4	5.4	5.5	5.5	N/A	N/A	5.5	5.5
	DMFL	Low Band	5.4	5.6	3.0	2.9	5.5	5.5	5.1	4.9	5.6	5.6
		High Band	5.4	5.6	5.5	5.6	5.5	5.5	N/A	N/A	5.5	5.6
Users	PHR	Low Band	5.2	N/A	2.9	2.9	5.6	5.6	5.6	4.7	5.5	5.4
		High Band	5.5	N/A	5.5	5.5	5.5	5.5	N/A	N/A	5.6	5.5
	PTH	Low Band	5.2	5.6	3.0	2.9	5.6	5.6	5.6	4.9	5.5	5.5
		High Band	5.6	5.5	5.5	5.5	5.5	5.5	N/A	N/A	5.6	5.6
	LRHR	Low Band	5.1	5.6	N/A	N/A	5.6	5.5	5.6	4.4	N/A	5.5
		High Band	5.4	5.5	N/A	N/A	5.5	5.4	N/A	N/A	N/A	5.6
	LRHL	Low Band	5.2	5.6	N/A	N/A	5.5	5.3	5.7	5.6	N/A	5.3
		High Band	5.5	5.6	N/A	N/A	5.4	5.5	N/A	N/A	N/A	5.5
	LRTH	Low Band	5.5	5.6	N/A	N/A	5.6	5.4	5.7	4.4	N/A	5.3
		High Band	5.6	5.6	N/A	N/A	5.5	5.5	N/A	N/A	N/A	5.5
	SAM and hand phantom	Low Band	5.4	5.6	2.9	2.9	5.6	5.6	5.6	4.4	5.7	5.1
		High Band	5.5	5.6	5.5	5.5	5.5	5.5	N/A	N/A	5.6	5.6

Table 5.15: Comparison of capacity results for different handsets and use case

In this table the capacity results with an SNR of 10dB are closed between the different handsets varying between 5.4 and 5.7 bits/Hz for the handset with two dual-band antennas (H1, H2, H5, H6, H11 and H12). Handsets with two dual-band antennas achieved the best capacity and are less sensitive to user influence. Moreover we can observe that capacity is in general higher for high band due to lower correlation in high band. These observations confirm the importance to obtain for the handset a lower correlation between antennas in order to perform higher capacity results. We will analyze this point more deeply in the next part.

5.4.2 Handset design

According to the results we can notice that handsets performing the best capacity for all the use case are handset 2,5,6 and 11. All these handsets have in common a BFF and two dual-band antennas. By looking the table we can observe that handsets with one mono-band antenna are performing a worst capacity than two dual-band antennas. In fact H3 and H4 perform a lower capacity in low band because they have only one antenna working in low band therefore we can consider that the MIMO system as a MISO one reaches a capacity close to 3 $[Bps/Hz]$. Also H14 which has two top low band antennas and a SFF achieves a lower capacity in FS than H5 which has also two top antennas and a BFF and is more sensitive to user interaction. Indeed H14 experiences a higher correlation when the user is interacting with it 5.2. We can observe the user impact by comparing landscape mode in right handling and in left handling. In LRHR the user is directly interacting with the two top antennas increasing the correlation of 0.7 in comparison with LRHL and therefore he decreases the capacity achieved by the handset of 1.2 $[Bps/Hz]$. In other words if handset design with two top antennas have less cases of direct interaction with users, such handset can be more sensitive with SFF. Therefore in order to reduce the risk of high correlation and lower capacity with two top antennas design it is better to choose a BFF handsets with two dual band antennas. That's why we can consider that the handset 5 have the best design to perform a good capacity with two top antennas. Handset with antennas which are located at the bottom and top or on the side of the handset perform also a better capacity with two dual-band antennas but the Form Factor have a lower influence on the capacity achieved. In fact when we look at the H11 and 12 even if H12 have a higher correlation values but lower BPR values than H11 their capacity achieved are closed for all the use case.

5.4.3 Correlation study

In this section we are interested on the correlation impact on the capacity achieved . We can see on the figure below 5.5 that a higher correlation decrease strongly the capacity of the MIMO system. The plots have been computed only for low band due to the constant low correlation for high band. The plots contains results of seventy-eight capacity measurements coming from ten handset and nine use cases in order to have general overview of correlation impact over random handset. Most of the capacity results have closed value (Table: 5.15) therefore a repartition bar chart have been added to the plot. More than 50 percent of the results have a correlation lower than 0.3 with 28 percents of the results having a correlation of 0.2. On this plots we can observe that even with a low correlation (under 0.5) we can observe low capacity with values closed to 3 $[Bps/Hz]$ These measurements are coming from handsets with two mono-antenna (H3 and H4) therefore the MIMO capacity is strongly reduced. The correlation value is an important parameters to achieved a good MIMO capacity however we can also wondering what is the BPR impact on the capacity that we will see in the next part.

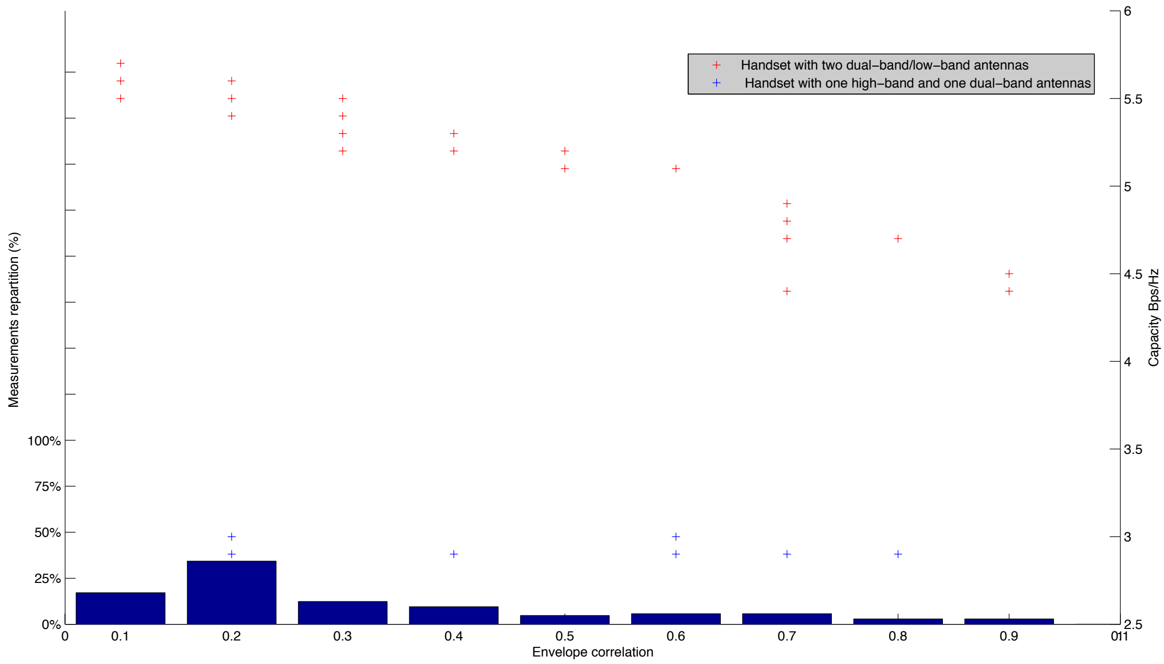


Figure 5.5: Capacity and measurements repartition with envelope correlation variation for low band. The red markers represent handsets with two dual band antennas or two low band antennas. The blue markers represent handsets with a dual band antenna and a mono band one.

5.4.4 BPR study

As studied in the last part the correlation variation have a strong impact on the capacity achieved by the system. However we have to study also the BPR impact on the channel capacity variation. The impact of BPR depends on which diversity technique is used but basically it is better to have a BPR value around 0 with small variation according to different use case in order to avoid error of channel estimation and branches with a too low SNR. The BPR have a limited impact on the channel capacity in comparison with correlation which involve a constant decrease of the capacity for higher correlation. In the BPR case we can observe some low capacity results even with a low BPR (see:5.6). However the BPR must not be too high in order to still achieved a good capacity. Basically according to our measurements results (see: 5.6) it should be under the absolute value of 13dB for all the use case. In fact for BPR values above 13dB the capacity seems to not performs above 3 $[Bps/Hz]$. Therefore above this threshold we can consider that the antenna diversity of the MIMO system is not anymore optimized to perform high capacity and can be considered as a MISO one.

As the correlation plots 5.5 on the figure below 5.6 we have plotted seventy-eight measurements coming from ten different handset and nine different use case. This plot allow us to have a global overview of capacity variation according to BPR evolution with random antenna design and use case. We have differentiate the handset with two dual-band/low-band antenna with red colors and handset with one high-band and one dual-band antenna in blue colors. In fact only handset two dual-band/low-band antennas are performing antenna diversity.

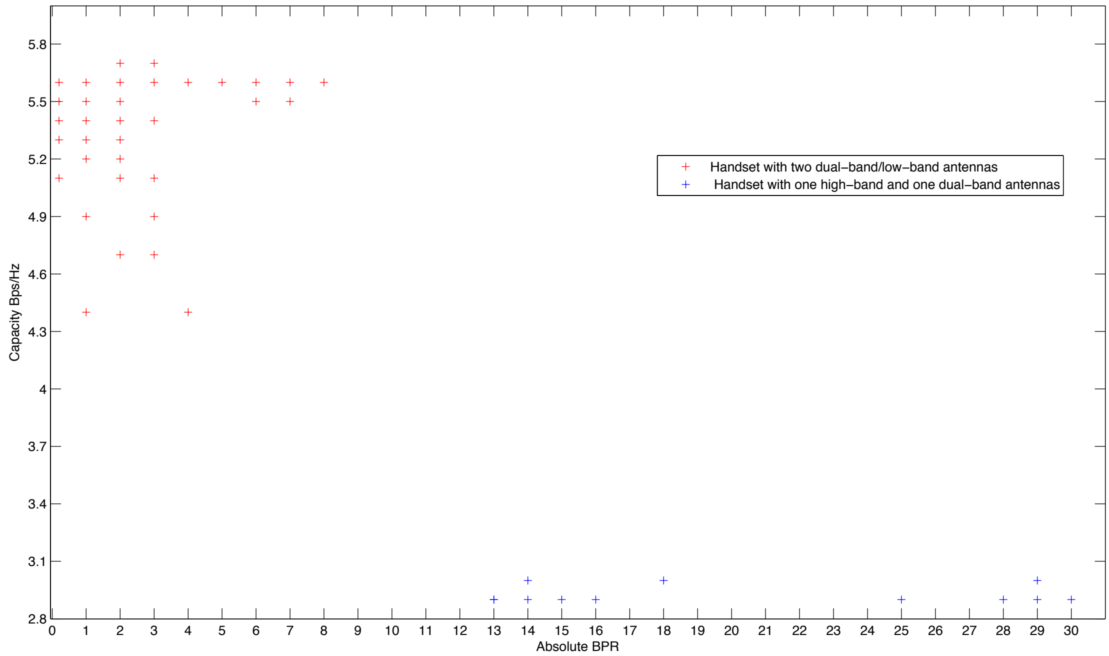


Figure 5.6: Capacity achieved according to BPR values for low band

We can consider that H12 H1 H14 and H5 are performing a low BPR 5.7 in all the case with small variation but as explained previously it is not necessarily linked to a good channel capacity performance. As we will see in the next plot we have represented the capacity variation of two handset H11 and H14 in different use case. H14 achieved antenna diversity but is performing a bad capacity however is BPR value remains low by don't exceeding 4dB for the worst case. In the meantime H11 accomplish a good capacity by having values above 5.1 $[Bps/Hz]$. However we can observe that BPR values reach 8dB for some case with still a good capacity. Therefore we can conclude that the BPR variations have a limited impact on the channel capacity and seems to decrease strongly the capacity when the BPR is higher than 13dB for system which can't use antenna diversity.

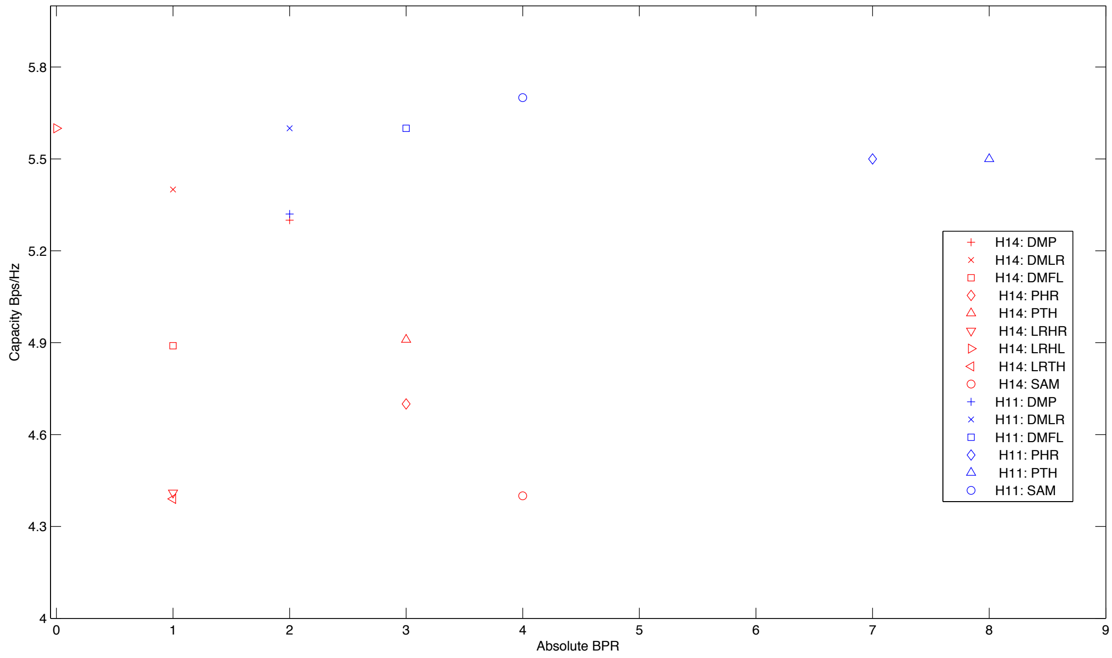


Figure 5.7: Capacity achieved for H11 and H14 according to BPR values and different use cases for low band

Conclusion

In this thesis report the performances of ten handsets have been studied and analyzed in order to see which of them have good antenna design and which ones don't in function of different use case. In particular the study has been divided in two parts: an analysis of the simulation results and an analysis of the data collected during a measurements campaign in downtown Aalborg. In the first analysis the performances of the antennas of two handsets(H11 and H12) have been studied in terms of envelope correlation, mean effective gain and received power. In the second analysis the parameters involved are envelope correlation, branch power ratio, received power and channel capacity.

Regarding the simulation part the study on the correlation leads to state that H11 and H12 experience a high correlation in low band in free space in all the three channel model considered: isotropic, Taga and AAU. The results are referred to mean values of envelope correlation. By considering the user the correlation decreases a lot going below the threshold of 0.5 in the firm grip while in soft grip the mean correlation values in Taga and AAU models are still above the threshold. In the high band the correlation is really low for both handsets and for all the channel models. Specially for H12 where it is 0 in most of the cases. The comparisons between the two handset does not leads to relevant variations. Indeed the values in free space are identical in low band and differ of 0.1 in high band. Phone form factor does not seem to impact the correlation from the simulation point of view.
The MEG of both handsets is constant for the isotropic channel either in free space either with the user interaction. Furthermore no relevant differences have been observed between H11 and H12 in free space in Taga or AAU model for low and high band. For both handsets the MEG is higher in low band due to the bigger distance between the antennas. H12 experience 1.2dB of difference between low and high band in Taga model and up to 3dB in AAU model. Adding the user implies a decrease of 0.5dB in Taga model and up to 1dB in AAU one. According to the simulation results user interaction seem to decrease the mean received power of the antenna for all the models studied.
The total received power of the two handsets is around 1dB in all the channel models. Only in the AAU received power of 1.3dB in free space and 1.6dB in soft grip has been observed. Looking at the power received in θ polarization we notice the user is always decreasing the reception of the power because he is blocking some incoming power in that direction. In ϕ polarization an opposite situation is noticed. The received power increases when the user is interacting with the mobile.
Hence in conclusion from the analysis of the simulation part it is possible to state that the two handsets does not experience variations in all the parameters studied in the three use case studied. The antennas of the two handsets have the similar performances.

In the analysis of the measurements' results the performances of the antennas of ten handsets have been investigated. We have examined also the impact of each antenna's characteristic such as different antennas locations, resonant frequencies, antenna type and form factor on the different parameters studied.

All the handsets have a correlation below the threshold which is 0.5 except H1 in free space, H14 in user case and H4 either in free space either in presence of the user. The handsets with the lowest correlation are H11, H3, H5 and H2 and they are not sensitive to the user interaction. Analyzing the influence of the different characteristics on the antenna design we notice that handset with high Q, top and bottom antenna on the long side, BFF and two dual band antennas experience low correlation, i.e. about 0.3 in free space and 0.2 in user case. Combining all these results we found that H11 respects these characteristics but also H2 and H5 are good mock-ups. Considering also the SAM and hand phantom it has been found that the values are similar to the correspondent handling with the real user. A maximum difference of 0.2 has been observed for H12. Moreover a comparison between the results obtained from the simulation and the ones from the measurements has been done. It shows that is not possible to state which channel model considered in the simulations the one that fits better with the real environment considered in the measurements campaign.

Concerning the received power more than one handset receive a signal with a good power level. Either in low band either in high band there are no significant differences to be considered between the handsets. The only exception is H4 in low band which receives much less power than all the other handsets. Further studies have shown that handsets with a dual band and a mono band antenna as H4 receive less power even if H3 presents a dual band and a mono band antenna but it receives a similar level of power of all the other handsets. However the antenna characteristics does not change the received power in a significant way. Hence it turned out that several handsets receive a good signal level in terms of power and probably the received power is a less important parameter than the others to see the differences in antenna performances.

About the BPR the results coming from the measurement showed high standard deviation between each handset and also each use case highlighting the importance of antenna design with the variation of the BPR. The BPR plays a key role in the antenna diversity performance of a MIMO system. Having a low BPR with small variation will allow to avoid branch with high SNR or errors of channel estimation according to which diversity combining technique is selected. According to our results the mean values with random handset in free space is equal to 2dB in low band and 1dB in high band. In the meantime the different user interactions increased the absolute BPR of 1dB in low and high band which was expected according to the MEG results in the simulation. We can conclude that the low band is more sensitive to reach higher BPR with higher MEG variation due to the environment and user interaction. Handsets with one high-band antenna and one dual-band antenna are performing BPR higher than 13dB in low band. These high results are expected as the handset is only receiving signal with one antenna in low band. Moreover as expected we didn't observe noticeable BPR variation in low band between handsets with two dual band antennas and handset with two mono band antennas. As the MEG variation depends on its environment we expected that BPR measurement at different room location will vary. We observed that the standard deviation of the BPR between different locations was varying between 2.5 and 0.1 for different use case. Moreover we didn't notice any strong standard deviation variation between high/low band and FS/user case. We can also add that some locations present higher standard deviation between handsets than other ones. These results highlight the impact of the locations in the environment on the antenna design. Besides on small handset the antennas location is a key factor on the BPR variation especially with user interaction. We can expect that BPR of handsets with two top antennas will interact in a different way than top and bottom antennas especially with user interaction. Handsets with two top antennas achieve a higher BPR in FS than top/bottom configuration. However top/bottom one is more sensitive to reach high BPR with user interaction. Moreover by computing the mean BPR of handsets with different Q we can observe that high Q handsets perform higher BPR than low one in FS and with user interaction. According to the results SFF handsets have lower BPR than BFF one in FS and with user interaction. Hence in order to achieve a low BPR for optimizing antenna

diversity it is better to use handset with dual-band antennas, two top antennas, low Q, e.g. H5.
The channel capacity variations of a MIMO system with two receivers, two transmitters and a SNR of 10dB have also been investigated in this report. Handsets with two dual-band antennas achieved the best capacity and are less sensitive to user influence. Moreover by not considering handsets with one mono band and one dual band antenna which can be considered as SIMO system, in FS the mean capacity achieved with all the handset is 5.3 $[Bps/Hz]$ in low band and 5.5 $[Bps/Hz]$ in high band. By adding the user interaction the capacity barely increases of 1 $[Bps/Hz]$ for low band and holds constant for high band. To conclude the channel capacity variations are low and therefore seems not to be too impacted by the user interferences. Moreover the high band seems to perform higher capacity in general due to the very low correlation experienced in the high band by all the handsets allowing to obtain independent channels. Knowing from previous studies that the high band has a constant low correlation we investigate the correlation and BPR impact on the variation of the channel capacity. As expected the correlation has a strong impact on the channel capacity. A constant decrease of the channel capacity measurements with higher correlation has been observed. Channel capacity lower than 5.1 $[Bps/Hz]$ is experienced when the correlation is higher than the threshold of 0.5. The BPR impact on the channel capacity variation is limited with respect to the correlation. We did not observe any clear capacity difference with low or high BPR. However with a BPR higher than 13dB we observed very low capacity for handsets with dual-band/high-band antennas. A very high BPR means the system is working as a SIMO one and therefore will strongly reduce the channel capacity. For a future work, in order to study deeply the BPR impact on the MIMO system a capacity study with different combining techniques like MRC, EGC, AC and with different level of SNR should have been added to this analysis.

At the end of this thesis concerning the performances of ten handsets in 4G-LTE scenario handsets 2, 11 and mostly 5 have been identified as the ones which present a good antenna design since they experience low correlation which in general leads to higher capacity. Despite the user interaction these three handsets still perform a good capacity. However H11 achieves high BPR values with user interaction which can strongly limit the efficiency of the system if combining techniques like MRC or EGC are used. These three handsets have all a big form factor, two dual band antennas, each of them has two antennas of the same type. The difference is in the Q which it is really high for H11 compared to the others and the position of the antennas.
The handset whose antennas perform worse is H4 because it has high correlation and very high BPR which leads to low channel capacity probably due to the presence of a mono band and a dual band antenna on it. It receives very low signal strength in low band and perform like a SIMO system in comparison with the other handsets.

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Appendices

Appendix A

Figure 5.8: Map of the measurement location

Figure 5.9: Example of firm grip [42]

Figure 5.10: Example of soft grip [42]

Appendix B

In this part we will have a brief presentation of the **Matlab** code used to treat the data coming from measurement and simulation campaign:

- *BPR all handsets positions.m and correlation all handset.m* : These files contains the BPR and correlation measurements data of the ten handsets studied in low and high band with nine different use cases. Each BPR and correlation values are the mean of the BPR values of the different users and room locations used in the measurement. The standard deviation calculation for each use case has also been added.

- *BPR H1 LA.m, BPR H11 LA.m and BPR H5 LA.m* : Contains the BPR measurements coming from the four location A,B,C and D of the room for nine use cases. Each BPR value is a computation of the mean of the four locations and a computation of the standard variation for each use case have also been added.

-*BPR H1.m, BPR H12.m and BPR H11* : In comparison with LA file here the BPR measurement for the different users

-*figure use case frequ.m* : This Matlab files contains data of the power received of the handset 12 coming from the simulation. We have used simulation data to follow the evolution of the power received in different polarization and use case depending of the frequency variations.

-*power received ant1 ant2 high.m and power received ant1 ant2 low.m* : These two files contain measurements data of the power received of the ten handset for antenna 1 and antenna 2 in different use cases.

An update of the *SFS.m* file have been also done by adding a button allowing to extract the simulations data into LaTeX table.