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Design and Simulation of Adaptive and Multi-Rate Massive MIMO Systems for Terahertz Band Communication

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Als meus germans, Eduard i Jaume,
per les aventures encara no escrites
Abstract

The communications in the Terahertz Band (0.06-10 THz) are a promising new paradigm for wireless communications in the next decade. Their large available bandwidth, combined with the development of graphene antennas, characterized by their reduced dimensions, will enable establishing systems in environments that were very limited until this moment due to technological limitations, such as nanocommunications, as well as will help to solve the overwhelming occupation of the electromagnetic spectrum, which limits the capacity for wireless communications.

The novelty of this technology implies the need for studying and improving diverse aspects of the systems, such as the channel characteristics, the transmitters and receivers, the modulation and the associated protocols, among others. New models and solutions should be developed and investigated to be applied in the Terahertz context.

Furthermore, in the last years the use of multiple antennas for transmission and reception, known as MIMO, has been extensively studied, for applications in increasing capacity, improving the signal-to-noise ratio or saving energy by concentrating the power in particular directions. When the number of transmitting or receiving elements is increased to the order of hundreds, we name it Massive MIMO.

In the first place, several configurations are developed to concentrate the power through beamforming, and thus prevent the high path losses that are found at these frequencies. The elements in the antennas are placed following 2D and 3D layouts, aligned in the three axes. The advantages of highly directive antennas are studied, which are basically an increase in the effective range of the links or an improvement in the received signal to noise ratio. In particular, we show how the use of hundreds of antenna elements increases in more than one order of magnitude the distance at which the communication is feasible, subject to the frequency at which the system is working.

Then, there are introduced various designs that enable the use of diverse power beams with the objective of enabling an environment of more than one user. We have named this technique Adaptive MIMO, and it is based once again in the use of hundreds of elements. Moreover, an interference analysis is conducted, in order to control the power leaked by the new beams into non-desired directions by measuring the power density. The capacity is studied subject to its dependence over the interference level that it is produced by the interactions of
the different beams. The main benefit of the use of Adaptive Massive MIMO with respect to Massive MIMO is its versatility thanks to the possibility of using more than one beam.

Finally, there are presented configurations that enable the use of more than one frequency in a single antenna, technique that we have denoted as Multi-Rate MIMO. By placing the elements of the antenna in the surfaces of a cube the multi-path propagations are reduced. The selection of the best frequencies for each communication range is discussed. The capacities of the systems are calculated according to the use of one or more frequencies, with different assumptions for power limitations. We show that the capacity may be increased by using antennas with elements of different lengths, as well as we can adapt the capacity for different needs.
Resum

Les comunicacions a la banda dels Terahertz (0.06-10 THz) prometen ser el nou paradigma de comunicacions inalàmbriques a la propera dècada. El seu enorme ample de banda, combinat amb el desenvolupament d’antenes de grafè de dimensions molt reduïdes, permetrà establir sistemes en entorns fins ara molt limitats per la tecnologia existent, tals com les nanocomunicacions, i a més a més ajudarà a solventar el problema de sobreocupació de l’espectre, que fita la capacitat dels enllaços sense cables.

La novetat d’aquesta tecnologia implicarà la necessitat d’estudiar i millorar diversos aspectes dels sistemes, tals com les característiques del canal, els transmissors i receptors, la modulació i els protocols associats, entre d’altres. Es deuen investigar i desenvolupar nous models i solucions per ser aplicats al context dels Terahertz.

D’altra banda, als darrers anys s’ha estudiat extensament l’ús de multiples antenes en transmissió i recepció, conegut com MIMO, i llurs aplicacions per incrementar la capacitat dels sistemes, combatre el soroll i estalviar energia mitjançant la concentració de potència en determinades direccions. Quan el nombre d’elements transmissors i receptors creix fins a l’ordre de les centenes, MIMO passa a denominar-se Massive MIMO.

En primer lloc, es desenvoluparan diverses configuracions per concentrar la potència mitjançant beam forming, i així combatre les altes perdues de propagació que es produeixen a aquestes freqüències. Els elements es disposen seguint configuracions en 2D i 3D, al llarg dels tres eixos. S’estudien els avantatges de tenir antenes directives, ja sigui per incrementar la distància dels enllaços o bé millorar la relació senyal a soroll. En concret, es mostra que l’ús de centenars d’elements a les antenes permet augmentar en més d’un ordre de magnitud la distància de l’enllaç, depenent de la freqüència de treball.

A continuació, es presenta el disseny d’una configuració que permet utilitzar diversos feixos de potència amb l’objectiu de servir a més d’un usuari. Aquesta tècnica l’hem denominada Adaptive MIMO, i es basa de nou en l’ús d’antenes amb elements a l’ordre de les centenes. A més a més, es realitza una anàlisi de les interferències introduïdes per aquests nous feixos, a nivell de distribució de potència. S’han obtingut també les diferents capacitats del sistema segons els nivells d’interferències que es produeixen depenent de la interacció entre feixos. El principal benefici de la utilització de Adaptive Massive MIMO respecte a Massive MIMO és la versatilitat introduïda a partir de l’aparició dels diferents feixos.
Per últim, es presenten configuracions que permeten treballar a distintes freqüències, tècnica que hem denominat Multi-Rate MIMO. En concret, s’ha introduït una nova disposició d’elements basada en la colocació dels elements en la superfície d’un cub. Es discuteixen les millors freqüències per les comunicacions depenent de la distància de l’enllaç. S’analitzen les capacitats dels sistemes d’acord amb l’ús d’una o vàries freqüències, assumint diferents limitacions en potència. Mostrem que podem incrementar la capacitat utilitzant antenes amb elements de diverses longituds, a més a més d’oferir una velocitat de transmissió adaptada a diferents necessitats.
Resumen

Las comunicaciones en la banda de Terahertz (0.06-10 THz) prometen ser el nuevo paradigma de comunicaciones inalámbricas en la próxima década. Su amplísimo ancho de banda, combinado con el desarrollo de antenas de grafeno de dimensiones muy reducidas, permitirá establecer sistemas en entornos hasta ahora muy limitados por la tecnología existente, tales como las nanocomunicaciones, y además ayudará a solventar el problema de sobreocupación del espectro, que acota la capacidad de los enlaces sin cables.

La novedad de esta tecnología conllevará la necesidad de estudiar y mejorar diversos aspectos de los sistemas, tales como las características del canal, los transmisores y receptores, la modulación y los protocolos asociados, entre otros. Se deben investigar y desarrollar nuevos modelos y soluciones para ser aplicados en el contexto de los Terahertz.

Por otro lado, en los últimos años se ha estudiado extensamente el uso de múltiples antenas en transmisión y recepción, conocido como MIMO, y sus aplicaciones para incrementar la capacidad de los sistemas, combatir el ruido y ahorrar energía mediante la concentración de potencia en determinadas direcciones. Cuando el número de elementos transmisores y receptores crece hasta el orden de las centenares, MIMO pasa a denominarse Massive MIMO. En este trabajo estudiaremos las aplicaciones del uso de Massive MIMO en la banda de los Terahertz.

En primer lugar, se desarrollarán diversas configuraciones para concentrar la potencia mediante beamforming, y así combatir las altas pérdidas de propagación que se producen a estas frecuencias. Los elementos se disponen siguiendo configuraciones en 2D y 3D, a lo largo de los tres ejes. Se estudian las ventajas de tener antenas directivas, ya sea para incrementar la distancia de los enlaces o bien mejorar la relación señal a ruido. En concreto, se muestra que el uso de centenares de elementos en las antenas permite aumentar en más de un orden de magnitud la distancia de un enlace, dependiendo de la frecuencia de trabajo.

A continuación, se presenta el diseño de un configuración que permite utilizar diversos haces de potencia con el objetivo de servir a más de un usuario. Esta técnica la hemos denominado Adaptive MIMO, y se basa de nuevo en el uso de antenas con elementos en el orden de las centenares. Además, se realiza un análisis de las interferencias introducidas por estos nuevos haces, a nivel de distribución de potencia. Se han obtenido también las diferentes capacidades del sistema según los niveles de interferencias que se producen dependiendo de la
interacción entre haces. El principal beneficio del uso de Adaptive Massive MIMO respecto a Massive MIMO es la versatilidad que se introduce gracias a la aparición de los distintos haces.

Por último, se presentan configuraciones que permiten trabajar a distintas frecuencias, técnica que hemos denominado Multi-Rate MIMO. En concreto, se ha introducido una nueva disposición de elementos basada en la colocación de elementos en la superficie de un cubo. Se discuten las mejores frecuencias para las comunicaciones dependiendo de la distancia del enlace. Se analizan las capacidades de los sistemas de acuerdo con el uso de una o varias frecuencias, asumiendo diferentes limitaciones en potencia. Mostramos que podemos incrementar la capacidad utilizando antenas con elementos de diversas longitudes, además de ofrecer una velocidad de transmisión adaptada a diferentes necesidades.
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Chapter 1

Introduction

1.1 The Terahertz Band

In the last years there has been a significant demand increase for speed in wireless communications. In spite of the continuous technological improvements that have come in hand with this fact, we observe that the frequency spectrum has become a limiting factor, with systems that cannot increase their capacity due to the theoretical limits associated to a given bandwidth \([1, 2]\). Hence, in order to achieve faster links, the solutions do not come through better modulations or codings, it is necessary to explore new frequency bands.

The Terahertz Band contains the frequencies between 0.06 THz and 10 THz. Note that in this definition we have included the frequencies known as millimeter wave, currently an interesting topic in the literature for providing new resources to wireless links \([3, 4, 5]\). There exist several reasons why this part of the electromagnetic spectrum is worth to be considered the solution for the shortage in bandwidth \([6, 7]\), which are explained in the following lines. On one hand, the frequency band immediately below cannot further enhance its capacity, in the order of Gbps, with the existing technology. This is because the already mentioned bandwidth problem. On the other hand, the infrared and optical systems present limitations due to the absence of adequate devices and the propagation characteristics in the air, which are very adverse.

Apart from the problems associated to other parts of the spectrum, the Terahertz Band presents some advantages by own merits. The combination of short pulses and simple modulations allows to save energy \([8]\). It is worth mentioning that the directivity of graphene antennas \([9]\) (which are still under development) is higher than the one that of the electric
dipoles usually used for lower frequencies. Finally, the bandwidth is not an issue any more. This available bandwidth heavily depends on the communication range [10], as we will explain later.

### 1.1.1 Applications

There is a wide range of scenarios in which wireless communications in the THz Band may be applied. The fact that this technology is entirely new and its differences with regard to existing systems may strengthen its use in environments in which communications were limited due to intrinsic inabilities of the existing methods. As an example of this, the use of nanoantennas [11] anticipates an evident growth in nanocommunications, while not preventing the possible application in macroscopic configurations.

Nanocommunications in the THz Band are enabled through the use of graphene nanoantennas. These type of communication is characterized by having devices in the order of $\mu$m and distances for the links up to 10 cm [12]. Among the multiple uses that may be conceived for them, we point out those related to health monitoring systems, based on sensors placed in the body; and also the communication among chips, essential for the development of multicore computer architectures.

In classical wireless communications the THz Band will allow an increase in capacity for the wireless cellular networks up to Tbps, which is orders of magnitude above the current technology. Also, it will be possible to set up Local and Personal Area Networks with the same capacity, in such a way that the last part of the access network will not be the bottleneck of the transmission with respect to the wired network. Finally, we point out the communication among devices as another possible application.

### 1.1.2 Channel Model

A novel channel model was proposed for the THz Band in [13]. It captures the remarkable differences that this frequency range presents respect to other parts of the spectrum. In particular, some gas molecules that compose the air vibrate when they are radiated with electromagnetic waves at THz frequencies, producing an effect known as molecular absorption [14]. The molecular absorption has two negative effects over the propagation: it attenuates the signal as it travels through the medium and it introduces molecular noise associated to the vibration itself. The power attenuation of the signal is given by the coefficient:

$$ A_{\text{abs}}(f, d) = \frac{1}{\tau(f, d)} = e^{k(f)d} $$
1.1. The Terahertz Band

where \( d \) is the distance covered by the signal, \( f \) is the frequency and \( k \) a coefficient that depends on the air composition (mainly the water molecules) and the frequency.

On another side, apart from the molecular absorption, we have the losses related to the spherical propagation of the wave: the spreading losses. The power attenuation for these losses are computed as:

\[
A_{\text{spread}}(f, d) = \left( \frac{4\pi fd}{c} \right)^2
\]

where \( c \) is the speed of light in the vacuum. By combining both expressions we obtain the total propagation losses in the THz Band, in dB:

\[
A(f, d)[\text{dB}] = 20 \log_{10} \frac{4\pi f}{c} + 10 \cdot k(f)d \cdot \log_{10} c
\]

The first term presents a logarithmic increase with the frequency, while the second is the cause of peaks for particular frequencies. We show this behaviour in figure 1.1, for different distances:

![Figure 1.1: Path Loss (dB) in the THz Band](image)

The figure above represents the channel response for a line-of-sight (LOS) link. The attenuations are high even for relatively short distances, and they increase with the frequency. This fact enhances the need for techniques that overcome these high path losses. We have presented this channel model because it will be used in the following chapters in order to dimension the range of the links.

The model for non-line-of-sight propagation needs some modifications, since it should take into account the reflection properties of materials. There exist studies that focus on
communications conducted using reflective mirrors [15, 16]. Also, multipath propagation was theoretically explored in [17], since the models for lower frequencies do not capture the peculiarities of the THz Band.

1.2 What is MIMO?

The use of multiple elements in the antenna in transmission and reception offers numerous advantages in wireless communications with respect to employing a single element antenna. Over the last decade these benefits have been extensively explored [18, 19, 20, 21], with the aim of increasing the resilience to fading, expand the link range or increase the throughput. When a system has more than one antenna available for transmission and reception it is known as multiple-input-multiple-output (MIMO).

Let us consider a system with $N$ transmit and $M$ receive antenna elements. We will denote $y$ as the received vector signal, $x$ as the transmitted vector signal, $H$ as the channel matrix and $w$ as the noise.

$$y = Hx + w \quad (1.1)$$

The channel matrix represents every SISO channel $h_{mn}$ between the $m$-th receiving and the $n$-th transmitting element:

$$H = \begin{pmatrix} h_{11} & \cdots & h_{1N} \\ \vdots & \ddots & \vdots \\ h_{M1} & \cdots & h_{MN} \end{pmatrix}$$

Depending on the proposed utilization of MIMO, diverse techniques have been developed in order to satisfy different needs. In the next part we discuss the most relevant among them. After that, we present some of the existing models used to implement those techniques. Finally, we focus on the specific application that is exploited in this work, known as beamforming.

1.2.1 MIMO Techniques

The purposes of use for systems with multiple antenna elements may be grouped in three sets:

- **Spatial Multiplexing Techniques**: Diverse informations are transmitted over each antenna with the aim of obtaining higher bit rates.
1.2. What is MIMO?

- **Spatial Diversity Techniques**: They are focused on the improvement of errors by means of coding gain and diversity gain.

- **Smart Antennas and Beamforming Techniques**: Multiple antennas are used to suppress interferences from other users or increase the signal to noise ratio.

**Spatial Multiplexing Techniques**

The utilization of multiple antenna elements in transmission and reception allows an increase in the maximum capacity of the system by a factor of $\min\{M, N\}$, being $N$ and $M$ the number of receiving and transmitting elements, respectively. It is necessary that we are working in a high SNR environment in order to obtain this linear increase in capacity [22].

The procedure followed so as to introduce in the communication this improvement in bit rate is described in the next lines, following the reasonings introduced in [23, 19]. We divide a sequence of bits in $N$ parts, which are modulated and transmitted over the same frequency band. In the receiver, these parts are separated by interference cancellation techniques.

Regarding the detection, there exist several algorithms that vary in precision and complexity. For those named linear, which consist of a matrix transformation, we demand the frequency response to the channel to be flat, and the number of receiving elements to be at least as that in the transmitting antenna. Examples of such schemes are zero-forcing (ZF) or minimum-mean-squared-error (MMSE).

The error rate is guaranteed through the channel coding, usually implemented when using multiplexing. This coding may be performed along two dimensions: the vertical dimension, which is referred to that taking place previous to the demultiplexer [24], and the horizontal [25], which entails using the channel coding in each element separately. It is possible to conduct a third coding by combining the vertical and horizontal [26].

Depending on the channel conditions, there exists the possibility that intersymbol interference (ISI) affects the communication. This problem may harm remarkably the performance of the system, as shown in [27] by analyzing the performance of the BLAST algorithm under the effects of interferences. A common solution to avoid this situation is to use multiple carriers in different subbands with flat frequency channel response, such it has been done in the OFDM schemes [28]. Interference among distinct subbands does not occur.

In summary, there exist numerous spatial multiplexing techniques that combine solutions to the difficulties encountered for sending independent informations over each transmitting antenna element.
Spatial Diversity Techniques

In the wireless communications environment we face an effect that degrades the transmitted signal, known as fading [29]. This effect has mainly two causes: the constructive and destructive interferences that take place due to multipath propagation in a rich scattering environment (fast fading), and the blocking of the communication because of objects with large size, such as walls or buildings (slow fading). The spatial diversity techniques are introduced to reduce the errors derived by the presence of fading [30].

Diversity in reception consists of the smart combination of the received signals in order to increase the signal-to-noise ratio (SNR) [31, 32]. In case of knowing the channel, this combination may be optimal. Note that for this application does not need more than one antenna element in the transmitter side.

The reciprocal to the former, diversity in transmission, is based on the transmission of redundant signals over the different elements. This may be combined with a coding known as space-time coding, because it utilizes both the temporal dimension as well as the elements. There exist multiple schemes that detail the transmission as well as the receiving algorithm.

Once again, in case the channel is such that there exists intersymbol interference, the benefits derived from diversity might be compromised. In this situation, we may consider the use of a multicarrier scheme combined with the space-time coding, or adapt the codes in a way that the problems concerning ISI will be solved.

Smart Antennas and Beamforming Techniques

The last group of MIMO applications is related to modifying the radiation pattern of the antenna in order to either enhance SNR or eliminate interferences coming from other users in a multiuser environment [33, 34]. This technique is based on the adjustment of the radiation pattern of the antenna through the variation of the coefficients that determine the feeding of each element.

With respect to the interference elimination, we may adapt the radiation pattern of the transmitters to produce radiation nulls in the directions of other users to which we want to avoid transmitting, while we point the maximums at the required directions. Reciprocally, the receivers will place their nulls in the angles of transmitters not involved in the communication.

Finally, the technique in which the rest of this work will be based is known as beamforming. It consists of concentrating the power in the direction at which we want to transmit,
1.2. What is MIMO?

and it allow to improve the SNR significantly. In particular, by means of the proper feeding coefficients, we produce constructive and destructive interferences that lead to the existence of diagrams with maximums in the favourable angles.

1.2.2 Existing Models

In the last years numerous models have been developed for MIMO systems. These may be classified in two categories: physical models and analytical models [35]. In the physical models the $H$ matrix is referred to the channel response exclusively, ignoring the influence that antenna elements exert. On the contrary, analytical models not only capture the effect of the channel, but also consider the impact that antennas cause over the signal.

In the next part we will present three models that show different approaches for the use of MIMO.

Singular Value Decomposition

Let $H$ be the channel matrix of a physical model. Consider its singular value decomposition (SVD) as $H = USV^H$, where $\{\cdot\}^H$ represents the transposed conjugate. The transmitted signal $x$ is codified in the form $x = Vx'$, while at the receiver the coding will be $y' = U^H y$. Then:

$$y' = U^H y = U^H (USV^H)Vx' + U^H w = Sx' + w$$

Hence, through the SVD of the channel matrix we have obtained parallel communication channels (its eigenvectors) that can be exploited independently by spatial multiplexing. However, it remains as an open question how to distribute the available power over the different directions in order to maximize the capacity of the system. These directions should be accompanied by beamforming in the radiation pattern of the antenna in order to enhance the SNR at the receiver.

Let $R_x = \mathbb{E}\{xx^H\}$ and $P_T$ the available power for transmission. Recall that $w$ represents the noise, with i.i.d Gaussian distributed coefficients with variance $\sigma^2$. According to Shannon’s formula for the capacity of the system, we have:

$$C = \max_{\{R_x : \text{Tr}(R_x) \leq P_T\}} \log_2 \det \left( I + \frac{HR_xH^H}{\sigma^2} \right)$$
By taking the SVD for $HR_xH^H$ this expression may be transformed to:

$$C = \max_{\{R_x: \text{Tr}(R_x) \leq P_T\}} \sum_i \log_2 \det \left( I + \frac{\lambda_{ii}}{\sigma^2} \right)$$

where $\lambda_{ii}$ are the eigenvalues of the decomposed matrix. Depending on the information available in for the transmitter, the power allocation will be more or less efficient. Hence, if the channel is known then the used technique is named water-filling, because it distributes the power according to the magnitude of each eigenvalue. In case that the channel state is not known, the power is splitted evenly among antenna elements.

**Kronecker Model**

The stochastic nature of the wireless communication channel imposes the need to consider the correlation of the channel matrix in order to understand the behaviour of a MIMO system. This correlation is defined as:

$$R_H = \mathbb{E}_H \{ \text{vec}(H)\text{vec}(H)^H \}$$

where $\mathbb{E}_H(\cdot)$ represents the expected value over $H$ and $\text{vec}(\cdot)$ the operator that converts a matrix into a column vector.

The problem derived from introducing in the model the correlation as it has been defined resides in the fact that it implies considering a very high number of parameters, thus complicating the resolution. This is the reason behind the existence of many alternatives for capturing the channel’s stochastic behaviour. In the Kronecker model presented in [36] the channel matrix is given by:

$$H = \frac{1}{\sqrt{\text{Tr}(R_{Rx})}} R_{Rx}^{1/2} G \left( R_{Tx}^{1/2} \right)^T$$

where $G$ is a random matrix with zero-mean circularly symmetric complex Gaussian distributed coefficients and $M \times N$ dimension, while

$$R_{Tx} = \mathbb{E}_H \{ (H^H H)^T \}, \quad R_{Rx} = \mathbb{E}_H \{ H H^H \}$$

In this model we observe that the possible effects derived from the influence among transmitting and receiving antennas are omitted, because this is how the correlation is computed. However, this assumption might not hold. The Kronecker model stands out due to its simplic-
1.2. What is MIMO?

It is possible to achieve good results with a limited number of antenna elements. As the number of elements rises, more complex models become suitable.

**Weichselberger Model**

The Weichselberger model [37] explores the structure of the spatial correlation obtaining its eigenvalues and eigenvectors to capture the significant directions of propagation. Let us consider:

\[
R_{Rx} = U_R A_R U_R^H, \quad R_{Tx} = U_T A_T U_T^H
\]

where \( U_R, U_T \) are eigenbasis for the spatial correlation matrices and \( A_R, A_T \) are semidefinite positive diagonal matrices. This decomposition is used for the equation that describes the model:

\[
H = U_R (\tilde{\Omega} \odot G) U_T^T
\]

Here \( G \) is again a random matrix with i.i.d. zero mean complex normal distributed elements and variance equal to 1, while \( \tilde{\Omega} \) is the channel matrix and can be computed by taking the square root of every element in \( \Omega \):

\[
[\Omega]_{m,n} = \omega_{m,n} = E_H \{|u_{R,m}^H H u_{T,n}^*|^2\}
\]

The increase in complexity with respect to the Kronecker model is compensated by its better performance. As in the previous one, we have assumed that the channel has a flat frequency response.

**Wideband Model**

In this last model we want to point out the importance of the frequency band at which our system is working. The models introduced so far assumed that the available bandwidth is narrow enough to consider the frequency response to be flat, so every SISO channel between two antenna elements was modeled by only one parameter. Thus, in case of having a frequency selective channel, we need to solve this limitation. There is more than one existing solution, here that given by Kafie et. al. is shown [38]. Other models can be found in [39, 35, 40]

In the time domain, let \( y[n] \) and \( x[n] \) be the received and transmitted signals in a MIMO system under a frequency selective channel. Then:

\[
y[n] = \sum_{j=0}^{J-1} \hat{H}_j x[n - j] + w[n]
\]
where \( \hat{H}_j \) represents the channel matrix associated to the \( j \)-th path of the resolvable paths. The full channel matrix then is:

\[
H(\tau) = \sum_{j=0}^{J-1} \hat{H}_j \delta(\tau - \tau_j)
\]

The frequency selectivity is captured through the use of the multipath characteristic of the environment. For every path the \( j \)-th channel matrix is computed as:

\[
\text{vec}(\hat{H}_j) = \sqrt{\frac{K_j}{K_j + 1}} \text{vec}(\mathbf{H}_j^d) + \sqrt{\frac{1}{K_j + 1}} R_j^{1/2} \text{vec}(\mathbf{H}_j^w)
\]

The first addend represents the deterministic component associated with the line-of-sight, in case this exists, with \( \mathbf{H}_j^d = a(\theta_R)a^T(\theta_T) \) the array responses, while the second addend corresponds to the Ricean fading term. In it, the matrix \( \mathbf{H}_j^w \) is composed of i.i.d. white Gaussian random coefficients and \( R_j \) is the correlation matrix computed as \( R_j = R_T^j \otimes R_{rr}^j \).

Although there are differences among the various models, we note that they also share remarkable similarities, such as the use of eigenvalues or the correlation for the channel matrix.

### 1.2.3 Beamforming: Phased Arrays

We may understand MIMO as a way of concentrating the radiated power in the desired direction. This technique is called beamforming [41]. By placing the antenna elements separated and fed in a particular way, it is possible to produce constructive and destructive interferences in the propagating electromagnetic fields in such a way that the power does not travel with the same strength in all directions, thus enabling spending less energy in transmitting. In this part of the introduction we will present the mathematical background that explains how this is possible, as described in [42].

Let us consider an antenna with \( N \) elements equally spaced a distance \( d \) along the \( z \) axis placed in the positions \( z'_n = nd \) fed by currents \( I_n, n = 0 \ldots N - 1 \) By means of the Fourier transform and the current density vector \( \tilde{J}(\hat{\mathbf{r}}) \) we obtain the radiation vector of the whole configuration:

\[
\mathbf{N}(\hat{\mathbf{r}}) = \tilde{\mathbf{N}}_0(\hat{\mathbf{r}}) \sum_{n=0}^{N-1} I_n e^{jkd\cos\theta}
\]

where \( \tilde{\mathbf{N}}_0(\hat{\mathbf{r}}) \) is the radiation vector of the equivalent antenna with only one element (\( \hat{\mathbf{r}} \) is the normalized position vector), \( k \) is the wavenumber and \( \theta \) the angle with respect to the axis.
1.2. What is MIMO?

The current coefficients $I_n$ are usually phasors of progressive phase $\alpha$:

$$I_n = a_n e^{nj\alpha}$$

From the radiation vector we may derive the rest of characteristics of the antenna, such as the electric field. The term in the exponential is denoted as the *electric angle*:

$$\psi = kd \cos \theta + \alpha$$

which leads to the following expression for the electric field:

$$\vec{E}(\vec{r}) = \vec{E}_0(\vec{r}) \sum_{n=0}^{N-1} a_n e^{jn\psi}$$

In the former equation for the electric field we observe that the diagram for the total antenna is the product of the basic antenna ($\vec{E}(\vec{r})$) and a factor that takes into account the interferences among the $N$ elements, which is a function of the current coefficients, the frequency and the separation among elements. This term is known as *array factor* (AF) and is equal to:

$$AF(\psi) = \sum_{n=0}^{N-1} a_n e^{jn\psi}$$

The array factor as expressed in the previous equation depends only on the current coefficients $a_n$. When the electric angle is transformed to the real angle $\theta$, this dependency lays on the parameters already mentioned. The AF satisfies the following properties:

- It is a periodical function in the $\psi$ angle with period $2\pi$, such that the coefficients of its Fourier series correspond to $\{a_n\}$.
- If the current coefficients $a_n$ are real and positive, the maximum of the array factor is at $\psi = 0$.
- Given that the angle $\theta$ indicates the radiation direction in space and it only takes values in $[0, \pi]$ we have:
  $$\psi \in [-kd + \alpha, kd + \alpha]$$
- For real and positive current coefficients, when the visible margin includes $\psi = 0$ and
$|\alpha| \leq kd$ the maximum of the radiation pattern is at:

$$\psi = kd \cos \theta_{\text{max}} + \alpha = 0$$

$$\theta_{\text{max}} = \arccos \left(-\frac{\alpha}{kd}\right), \quad |\alpha| \leq kd$$

**Current Distribution.** As we have seen, the current coefficients play an important role for developing radiation patterns that satisfy our requirements. There exist different ways for feeding the antenna elements, here we will present a very typical one known as uniform. In the uniform distribution all elements are fed with the same amplitude $a_n = 1$. Further analysis of the equations leads to:

$$|\mathbf{A}\mathbf{F}(\psi)| = \left| \frac{e^{jN\psi} - 1}{e^{j\psi} - 1} \right| = \frac{\left| \sin \left( \frac{N\psi}{2} \right) \right|}{\left| \sin \frac{\psi}{2} \right|}$$

Also, for the secondary lobes and the beamwidth we have:

$$\text{NLPS} \approx N \left| \sin \left( \frac{3\pi}{2N} \right) \right|, \quad \Delta\psi_c = \frac{4\pi}{N}$$

The uniform distribution is the distribution that has maximum directivity and minimum beamwidth for a given antenna array. These two metrics regarding an antenna are defined as follows:

- **Directivity.** The *directivity* of an antenna is defined as the ratio of the radiated power density in a direction $(\theta, \varphi)$ over the equivalent power density of an isotropic antenna:

$$D(\theta, \varphi) = \frac{P(\theta, \varphi)}{P_i \frac{4\pi}{4\pi r^2}}, \quad D = \frac{P_{\text{max}}}{P_i \frac{4\pi}{4\pi r^2}}$$

If the direction is not specified, the directivity is understood to be the one corresponding to the maximum power density, $P_{\text{max}}$.

- **Beamwidth.** The *beamwidth* of an antenna is the angular dimension of the main lobe in its radiation pattern. In our case we will consider the limit of the lobe when the radiated power density is dropped to half of its maximum value.
1.3 Motivation and Overview of the Thesis

The Terahertz band offers multiple possibilities and applications in wireless communications. However, the propagation characteristics of this frequency range pose new unresolved challenges. In particular, the high path losses caused by molecular absorption and spreading losses should be compensated in order to enable the communication.

In the last decade there have been developed systems that use multiple antennas in transmission and reception. These provide with enhanced capacity, less errors and improvement in SNR, among others. Such systems could be used in order mitigate the propagation losses or allow multiple users, which are existing problems in the Terahertz band.

The aim of this work consists of exploiting and extending the MIMO applications in the THz band. We are specially interested in understanding the advantages of beamforming, either in single user or multi user environments. In order to conduct this work we have used the simulation tool COMSOL, which allows the modelization of radiofrequency systems.

The rest of this work is organized as follows. In chapter 2 we present the most important concepts related to the conducted simulations, classified in three categories: Massive MIMO, Adaptive MIMO and Multi-rate MIMO. In chapter 3 we introduce the tools that will be used for developing the simulations, contained in the COMSOL software. In chapter 4 we performed the Massive MIMO simulations, focused in enhancing the directivity. In chapter 5 we present the Adaptive MIMO simulations, which study multi-user configurations. The Multi-rate MIMO configurations are developed in chapter 6, related to the use of different frequencies in an array. Finally, in chapter 7 the work is closed by pointing out unsolved problems and stating final conclusions.
Chapter 2

Massive MIMO

2.1 Introduction

2.1.1 From MIMO to Massive MIMO

As it has been mentioned in the introduction, there are numerous MIMO models adapted to the diverse techniques that this technology suggests. Due to the channel characteristics in the THz band, we are interested in increasing the effective range of links using beamforming.

The MIMO systems are characterized by having up to tens of radiating elements in their transmit and receive antennas, fact that limits their potential directivity, since this metric is closely related the total electrical length. This is the reason behind the idea of increasing the number of elements to the order of the hundreds, which is a technique known as Massive MIMO.

There exist a few Massive MIMO implementations in the microwave band [43, 44], used in a multi-user and multi-frequency environment. These implementations only enable Massive MIMO in the base station side, since the terminals are not big enough to contain such arrays in that frequency. Given the short wavelength that characterizes the THz band, it is possible to include arrays with more elements without the space limitation being a problem.

2.1.2 Arrays in 2D and 3D

One of the challenges that we face in the implementation of Massive MIMO with linear arrays is their size. An array with a number of elements in the order of the hundreds and spacing of
half the wavelength will be too big for some applications. Also, by aligning the elements in a single axis we cannot direct the power with more precision than the angle that the desired point forms with the axis and the origin: the power diagrams present axial symmetry with respect to the imaginary line formed by the elements, as shown in the equations described in the introduction.

With these two problems in hand, the antenna size and the ability of aiming the power, we should consider alternative configurations for the Massive MIMO arrays. The suggested solution in this work consists of taking advantage of more dimensions for placing the elements of the arrays, and thus obtaining arrays in 2D and 3D.

In the 2D array case, the radiating elements will be placed in the XY plane shaping a grid along the $x$ and $y$ axes, with equally spaced elements by $\lambda/2$ in both directions, with $\lambda$ the wavelength of the central frequency of the modulation or the transmitted pulse, in case of using a carrierless scheme. Regarding the 3D arrays, the elements will be placed in a cubic shape configuration along the three axis $x$, $y$ and $z$ and equally spaced in each direction.

**Beam-steering**

The other problem related to the use of linear arrays is their incapability of directing the power with more precision than the given by the angle with respect to the antenna axis. This symmetry is broken when 2D and 3D arrays are utilized. Every direction is univocally determined by the angle that it forms with the axis in the antenna, and since there is more than one, there exists no axial symmetry.

However, it is also true that there exist back lobes for certain directions even in this configurations. The back lobes are lobes with a power magnitude comparable with the main lobe and they appear when the linear arrays in each axis propagate in directions that present symmetry. Their main disadvantages are that they detriment the directivity and produce interferences in undesired directions. It is worth mentioning that for the linear arrays the main lobe was symmetrical for all the axis, which means that the main lobe was pointing the same power around the axis for that particular angle, a situation worse than a back lobe.
2.1. Introduction

**Space Reduction**

As it has been mentioned, we need to take into consideration the total antenna size when implementing a Massive MIMO array. The proposed 2D and 3D configurations address this problem and achieve a considerable reduction of the size since the growth in placed elements is quadratic and cubic with the maximum size in a single dimensions. In figure 2.1 we show the growth in number of elements for the three different configurations.

![Figure 2.1: Number of Elements in Array](image)

**2.1.3 Applications in Lower Frequencies**

We have mentioned that there exist Massive MIMO models for lower frequencies given in [45, 46, 43], as well several measurement campaigns provided in [47, 48, 49]. We will describe the models concerning this technology and then point out the differences with respect to its application in the THz band. Let us consider a system with a time-invariant and narrowband channel such as

\[
y = Hx + w,
\]

where each term corresponds to the one given in equation 1.1. If we assume independently identically distributed gaussian transmitted signals with perfect channel state information at the receiver, then the capacity of the system, according to [50], is:

\[
C = \log_2 \det \left( I + \frac{P_t}{N_0} HH^H \right),
\]

with \( H \) normalized as \( \text{Tr}(HH^H) = MN \), \( P_t \) the transmitted power and \( N_0 \) the noise power. Hence, the capacity for the system is given by the distribution of the eigenvalues of \( HH^H \), as it occurred for MIMO. Assuming that the rows of \( H \) are asymptotically orthogonal, we can deduce that the capacity grows linearly with the number of elements (at both sides).

In order to achieve this increase in capacity, we need to perform several steps, such as the
channel estimation, coding or interference cancellation (ISI, pilot contamination). These are accomplished by adapting the models used in MIMO or introducing new techniques, but since our scenario for the THz band is different, we need to assess how to conduct this adaptation.

There are two main variations between the use of Massive MIMO for lower frequencies and our implementation in the THz band. In the microwaves, it has been stated that the typical environment is a cellular system with multiple users that should be served independently, by means of the pool of available frequencies. For our part of the spectrum, the first objective and motivation was to enable the communication itself by increasing the link range. This is conducted through the concentration of the power in a specific direction using large arrays with hundreds of elements. So a multi-user environment should be addressed in a further interpretation of the applications provided by these large arrays, as we will do in Adaptive MIMO.

In the situation of having a single-carrier scheme (or pulse) that directs the power in a single angle to a unique user, the most suitable model for the channel matrix is the Wideband Model, presented in the introduction. In it, the channel matrix was composed of several taps, according to a decomposition in flat fading subchannels. Each channel matrix should be estimated independently.

In this chapter we will develop and study a set of Massive MIMO antennas. As we will explain later in this chapter, Massive MIMO is the concept used for referring antennas with a large number of elements, typically greater than a hundred.

## 2.2 Theory

### 2.2.1 2D Configurations

An antenna array is considered to be 2D when its elements are located and distributed along both the $x$ and $y$ axes. As it has been pointed out, this technique provides the advantage of reducing the space occupied by the antenna, since the growth in number of elements translates into a growth in area and not only length.

As shown in figure 2.2, in this section we will consider that all elements are equally spaced $\frac{\lambda}{2}$ where $\lambda$ is the wavelength of the central frequency of our antenna design. For these simulations the main beam is aimed in the horizontal plane with $\theta = \frac{\pi}{2}$ and the azimuth angle $\varphi$ ranging from 0 to $2\pi$. The red dots represent the antenna elements, located aligned with the axes. Let us consider a numbering in the elements following the grid provided by figure
2.2. Theory

2.2, which consists of a pair \((m,n)\) where \(m\) represents the \(m\)-th column and \(n\) the \(n\)-th row, beginning from the bottom right corner. The array factor (AF) of the antenna is given by:

\[
\mathbf{AF}(k_x, k_y) = \sum_{m=1}^{M} \sum_{n=1}^{N} I_{mn} e^{j(m-1)k_x d_x} e^{j(n-1)k_y d_y}
\]

where \(M, N\) are the number of elements in the \(x, y\) axes respectively, \(k_x, k_y\) represent the \(x\) and \(y\) wavenumber components and \(d_x, d_y\) correspond to the separation between elements in the \(x\) and \(y\) axes.

The second dimension introduces a new degree of freedom. In a linear array we have the \(\alpha\) angle that captures the phase increase inserted for enabling the beamforming, while in a 2D array the phase will be modified by \(\alpha_x\) and \(\alpha_y\).

\[
I_{mn} = a_{mn} e^{j(m-1)\alpha_x} e^{j(n-1)\alpha_y}
\]

By defining \(\psi_x\) and \(\psi_y\) as the electric angles we obtain:

\[
\psi_x = kd_x \cos(\varphi) + \alpha_x = \pi \cos(\varphi) + \alpha_x \\
\psi_y = kd_y \sin(\varphi) + \alpha_y = \pi \sin(\varphi) + \alpha_y
\]

where \(k\) is the wavenumber.

The feeding of the antenna will be uniform: \(a_{mn} = 1\) \(\forall m,n\). Then the array factor becomes separable and we can treat the 2D array as a linear array in \(y\) built using a linear array in \(x\).

\[
\mathbf{AF}(\psi_x, \psi_y) = \sum_{m=1}^{M} e^{j(m-1)\alpha_x} \sum_{n=1}^{N} e^{j(n-1)\alpha_y} = \mathbf{AF}_x(\psi_x) \cdot \mathbf{AF}_y(\psi_y)
\]

Finally, we need to consider how to direct the main lobe of the linear arrays in \(x\) and \(y\). For any linear array with phase change \(\alpha\), the lobe is directed to the angle \(\gamma\) with respect to the axis formed by the elements when \(\alpha = -\pi \cos(\gamma)\). In particular, we should convert the cylindrical coordinate \(\varphi\) to the angle with respect to the axis:

\[
\gamma_x = \varphi \quad \Rightarrow \quad \alpha_x = -\pi \cos(\varphi) \\
\gamma_y = \frac{\pi}{2} - \varphi \quad \Rightarrow \quad \alpha_y = -\pi \cos\left(\frac{\pi}{2} - \varphi\right)
\]
2.2.2 3D Configurations

Antenna arrays are categorized as 3D if their elements span in the three space coordinates $x$, $y$ and $z$. Together with 2D arrays, this fact makes the 3D arrays more compact than linear arrays, in which the elements are placed considering a single dimension. The main feature that has changed from the previous simulations is that in the following configurations not only the arrays but also the propagation is conducted in a three-dimensional space.

We observe in figure 2.3 that a direction is determined by the spherical coordinates pair $(\theta, \varphi)$, while the elements in the array are equally spaced $\frac{\lambda}{2}$ where $\lambda$ is the wavelength of the central frequency of the designed antenna. The 3D antenna is built by stacking $P$ 2D-arrays separated half a wavelength. Although it is theoretically feasible to beamsteer the main lobe of a 2D-array for $(\theta, \varphi)$, the limitations of the simulations performed do not allow this. For our 3D antennas we will consider $(\theta, \varphi) \in [0, \pi] \times [0, 2\pi)$, hence the set of all possible directions.

[Diagram of 3D Array for Massive MIMO]

The numbering proposed for our 3D configurations is composed by $(m,n,p)$, representing each component the position in the axes $x$, $y$ and $z$ respectively. We need to extend the Array Factor calculation for the 3D case, taking into consideration also the variations produced by the $z$ axis:

$$AF(k_x, k_y, k_z) = \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{p=1}^{P} I_{mnp} e^{j(m-1)k_x d_x} e^{j(n-1)k_y d_y} e^{j(p-1)k_z d_z}$$

where the notation is analogous to that presented in the previous section. Following a parallel reasoning to the one shown for the 2D case, now there are three degrees of freedom, namely, $\alpha_x$, $\alpha_y$, and $\alpha_z$, which agree with the phase changes in each axis:

$$I_{mnp} = a_{mnp} e^{j(m-1)\alpha_x} e^{j(n-1)\alpha_y} e^{j(p-1)\alpha_z}$$

In order to compute the electric angles and steer the power in the targeted direction, we need to convert the spherical coordinates $(\theta, \varphi)$ into the angle that this direction forms with
2.3 Simulations

each axis \((\gamma_x, \gamma_y, \gamma_z)\):

\[
\gamma_x = \arctan \left( \frac{\sqrt{\cos^2(\theta) + \sin^2(\varphi) \cos^2(\theta)}}{\cos(\varphi) \sin(\theta)} \right)
\]
\[
\gamma_y = \arctan \left( \frac{\sqrt{\cos^2(\theta) + \cos^2(\varphi) \cos^2(\theta)}}{\sin(\varphi) \sin(\theta)} \right)
\]
\[
\gamma_z = \theta
\]

2.3 Simulations

We will contribute with various configurations applying 2D and 3D layouts, discussing their main features and stressing their advantages and drawbacks. These are the studied set ups:

<table>
<thead>
<tr>
<th>2D Configurations</th>
<th>3D Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(12 \times 12 = 144) antenna elements</td>
<td>(5 \times 5 \times 5 = 125) antenna elements</td>
</tr>
<tr>
<td>(15 \times 15 = 225) antenna elements</td>
<td>(6 \times 6 \times 6 = 216) antenna elements</td>
</tr>
</tbody>
</table>

Table 2.1: Massive MIMO configurations

2.3.1 12×12 Antenna Array

The simulation of the 12 × 12 array captures the theoretical results presented above. Our first experiment has consisted of building two linear arrays: one vertical \((y)\) and one horizontal \((x)\), for finally implementing a 2D array. We have computed their array factors and plotted them in figure 2.4 for the angle \(\varphi = \frac{\pi}{3}\), where it is shown that the AF of the 2D array is the product of the two linear arrays.
Figure 2.4: Array Factor Product

Provided that our antenna is able to beamsteer the power to a specific direction in the horizontal plane $\theta = \frac{\pi}{2}$, it is interesting to illustrate how this is done for diverse angles, as in figure 2.5:

![Figure 2.5: Array Factor for various $\varphi$](image)

In order to understand the accuracy that we need when pointing the beam to a direction $\varphi_0$, it is relevant to compute the beamwidth of the main lobe. As the shape of the radiation pattern varies with the horizontal angle, this angular width depends on it, however, there are very little variations and we may consider as constant for a 3dB decay:

$$\Delta \varphi_{-3\text{dB}} = 8.6^\circ$$

### 2.3.2 15×15 Antenna Array

We have also studied an antenna with 15×15 elements. The behaviour of this antenna is equivalent to the one previously developed in terms of the total array factor as a product of the two linear arrays in the $x$ and $y$ axes. In figure 2.6 we present the AF when varying the angle $\varphi$ for the maximum directivity.
2.3. Simulations

Regarding the beamwidth, an increase in the number of elements in the array helps to narrow the main beam, which is interesting in terms of directivity but makes aiming the antenna at the right direction more challenging. The beamwidth is independent of the targeted angle $\varphi_0$ and equals:

$$\Delta \varphi_{-3dB} = 6.9^\circ$$

The main to secondary lobe ratio is very similar to that for the $12 \times 12$ antenna, since as the number of elements goes to infinity this value stabilizes and only depends on the current distribution. For our simulations we have chosen a uniform distribution, this value is around 13.4 dB for a linear array.

In figure 2.7 we notice the dependence of the maximum directivity on the angle $\varphi$ to which the beamsteering is directed. This effect accounts for the fact that for linear arrays in $x$ and $y$ axes the two main lobes overlap when the desired propagation angle is close to axes ($\varphi \approx 0, \pi/2, \pi, 3\pi/2$), while they point distinct directions in the other cases.
2.3.3 5×5×5 Antenna Array

The 5×5×5 antenna array is shown in figure 2.8, in which we observe the 5 stacked layers of 2D arrays and the surrounding sphere as boundary. The beam may be steered in the two angles \((\theta, \varphi)\). With respect to the basic in the antenna element, it is worth mentioning that all the electric point dipoles are oriented in the \(z\) axis. Because of their radiation pattern of the form \(P(\theta, \varphi) = P_{\text{max}} \sin^2(\theta)\), this design will not be capable of steering the energy towards directions with \(\theta \approx 0, \pi\). In the simulations this radiation pattern is considered together with the total array factor and in the results is reflected accordingly.

In figure 2.9 we observe the simulation of the antenna when the beam is steered towards the direction \((\theta, \varphi) = (\frac{\pi}{2}, \frac{5\pi}{4})\). The shape and coloring of the plot indicate how the power density is distributed. For high densities we have a red and long beam, while for low power densities the lobes are represented in blue and close to the origin. In this simulation we notice a main beam in the targeted direction and several smaller beams.

As we discussed for the 2D arrays, it is interesting to understand the beamwidth of the obtained main lobe, since this will have an impact in the precision needed for aiming the antenna, as well as in the overall directivity. Due to the fact that the beam is a product of the array factors in the three coordinates, its width will depend on the chosen direction \((\theta, \varphi)\). We have computed the beamwidth for a 3 dB decay for \(\theta = \frac{\pi}{2}\) and observed that it is nearly independent of the \(\varphi\) angle.

\[
\Delta \varphi_{-3\text{dB}} = 20.6^\circ, \quad \Delta \theta_{-3\text{dB}} = 20.1^\circ
\]

The beamwidth narrows if a different \(\theta\) is taken, because of the observed increase in directivity that we will show in further calculations.
2.3. Simulations

2.3.4 6×6×6 Antenna Array

Our last massive MIMO configuration is a 6×6×6 antenna, represented in figure 2.10. The structure of it is equivalent to the one explained in the previous subsection, with 6 layers of 2D arrays spaced by half a wavelength. We have conducted a simulation of this antenna for a beam directed to \((\theta, \varphi) = (\frac{2\pi}{3}, \frac{3\pi}{4})\), with results for the electromagnetic far-field shown in figure 2.11. Despite the plot limitations, we observe a main lobe pointing the requested angle and a few smaller lobes in other directions. As we will see, the directivity of this configuration is significantly higher than the one of 125 elements, but the price paid for it is a more complicated system due to the increase in elements (nearly doubled).

In relation to the beamwidth of this configuration there are two considerations to be emphasized. First, as for the previous case, we have obtained the beamwidth of the main lobe for a 3 dB power loss with respect to the maximum in the horizontal plane, i.e. \(\theta = \frac{\pi}{2}\) and observed that it is approximately constant for all angles:

\[\Delta \varphi_{-3\text{dB}} = 17.2^\circ, \quad \Delta \theta_{-3\text{dB}} = 17.2^\circ\]

And also, as mentioned in the 5×5×5 configuration briefly, the beamwidth narrows as the lobe is directed to the vertical axis \(z\). Maximum directivity and beamwidth are very close concepts: if maximum directivity is large, then the beamwidth must be thin. In the following figures we will study the directivity and we will show that it increases when taking \(\theta \neq \frac{\pi}{2}\).

For the 2D case we illustrated the dependence of the array’s directivity over the angle \(\varphi\) as a consequence of the overlapping of lobes in the linear arrays in the axes \(x, y\). Now, in the 3D case, the calculation of the directivity becomes a bit more complex, as explained in the first chapter. In order to comprehend how the main lobe and hence maximum directivity is formed, we need to recall the array factor of a linear array. In a linear array, the power is radiated with an angle \(\gamma\) with respect to the imaginary axis configurated its elements, and the pattern has rotational symmetry around this axis.

Figure 2.10: 6×6×6 Antenna Array

Figure 2.11: 6×6×6 Beam
When we combine three linear arrays in the $x$, $y$ and $z$ axes (as the AF is the product of these three) the rotational symmetry disappears. However, as shown in figure 2.12, directivity still depends on the horizontal angle $\phi$. This is because for the angle $\theta = \frac{\pi}{2}$ the lobes for the $x$ and $y$ axes overlap in the same ranges than it happened in the 2D case. In this figure we demonstrate the maximum directivity as a function of the angle to which we point the main lobe for the two studied antennas: $5 \times 5 \times 5$ and $6 \times 6 \times 6$. There is nearly a factor two between the maximum directivity when radiating in favourable directions as opposed to directions with overlapping lobes. By modifying the altitude angle to propagate not in the horizontal plane, the directivity stabilizes around a value close to the maximum for $\theta = \frac{\pi}{2}$. As an example, we have taken figure 2.13, which corresponds to the maximum directivity as a function of $\varphi$ when $\theta = \frac{\pi}{3}$.

Finally, we want to point out that it is not possible to transmit power in the vertical direction, this is $\theta \approx 0, \frac{\pi}{2}$, because of the radiation pattern of the electric point dipole. There is an effective range for our configuration that is smaller than the proposed $(\theta, \varphi) \in [0, \pi] \times [0, 2\pi)$. If we take $\sin^2(\theta) = 1/2$ to be the limits, then this range becomes:

$$ (\theta, \varphi) \in \left[ \frac{\pi}{4}, \frac{3\pi}{4} \right] \times [0, 2\pi) $$
2.4 Performance Evaluation

In this section our objective is to demonstrate the advantages obtained from the use of Massive MIMO in a communication system in the THz band. We have mentioned that through the beamforming technique and by feeding the antenna elements adequately, it is possible to create a constructive interference in the proper direction that enhances the directivity, with the resulting diminishing of the path loss.

Let us consider a link with a separation distance of $d = 0.1 \text{m}$. Due to the channel properties, the propagation losses depend on the frequency at which the wave is traveling. In figure 2.14 (left) we show this fact. The graph in blue represents the path loss for the case of an antenna with no directivity ($D = 0 \text{ dB}$). In red and green we observe the functions for the 2D configurations, with $N = 12$ ($D = 17.4 \text{ dB}$) and $N = 15$ ($D = 18.3 \text{ dB}$) elements respectively. We have taken a mean value for their directivity, because as shown in former sections, this depends value depends on the $\varphi$ angle.

Figure 2.14: Path Loss for 2D and 3D Antenna Configurations with $d = 0.1 \text{ m}$

In figure 2.14 (left) we repeat the procedure from last paragraph for the 3D configurations, with directivities $D = 18.3 \text{ dB}$ and $D = 20.3 \text{ dB}$ colored in green and red respectively, taking once again a distance of $d = 0.1 \text{m}$ as reference. It is worth mentioning that the reduction in path loss will not result in an equal increase in distance for the whole spectrum, because the molecular absorption peaks will prevent an increase for certain frequencies.

In order to demonstrate this fact, we conduct the following experiment: we determine a maximum path loss for certain operative link, such as $\max(PL) = 40 \text{ dB}$. We calculate for each frequency the maximum distance that can be achieved by allowing this path loss, by
means of inverting the path loss function for each frequency $f_0$:

$$PL(f_0, d)[\text{dB}] = -20 \log_{10} \left( \frac{c}{4\pi f_0 d} \exp \left( -\frac{1}{2} k(f_0)d \right) \right)$$

As we know, the computed distance will be different in each case, as shown in figure 2.15 by the blue graph. Now, we consider the system to be provided with an antenna of directivity $D = 18$ dB, a value similar to those of our proposed configurations. Then the distance reached by the link will vary accordingly, because the receiver is allowed a total path loss of 56 dB. Also, if the system were provided with two massive MIMO antennas, one at the transmitter and one at the receiver, both with a directivity of $D = 18$ dB, then the total directivity of given both antennas would double, increasing even further the distance for the link. The graphs for these set ups are plotted in the aforementioned figure. In it, we realize that there are several low peaks that correspond to particular frequencies in which molecular absorption is specially critical. These results highlight the importance of choosing the proper set of frequencies in this band, because the range of the communication heavily depends on it.

Figure 2.15: Distance for a link with $\max(PL) = 40$ dB
2.5 Conclusions

In this chapter we have developed and simulated a group of Massive MIMO configurations in order to study their properties and features with the aim of possibly implementing this technique to solve the challenges addressed by communications in the THz band. The main contributions found in this chapter are:

- Antenna designs that provide with high directivities, using layouts in two or three dimensions, reducing the necessary space for the antennas. The antennas allow to aim the power at specific directions,

- The application of these designs to increase the effective range of links or improve the SNR at the receiver.

- A discussion over the need of selecting the proper frequency according to the path loss and directivity of the antenna.

In the first section we have presented general notions of 2D antenna arrays and their theoretical differences with respect to linear arrays. Also, two 2D antenna arrays have been computed using a 2D environment. In particular, we have discussed a 12×12-element and a 15×15-element antenna. In the horizontal plane, with these antennas it is possible to beamsteer the power to a targeted direction with a very narrow beamwidth, hence reducing interference with other users and saving energy to the enhanced transmitted power due to the maximum directivity achieved. Even though the beamwidth is constant in the whole range, for some angles there is a backlobe that is detrimental to the directivity.

The second section has extended the study to the third dimension by considering 3D antenna arrays and the propagation in a 3D space. Although the mathematics become more complex in these conditions, we were interested in understanding the antennas when radiating in the vertical angle θ, and hence it was necessary to study a 3D context, so we have introduced the equations for feeding the 3D antenna arrays. We have developed two configurations: a 5×5×5 antenna array and a 6×6×6 antenna array. The main advantage of these simulations is the possibility of exploiting the altitude angle for directing the beam also in this coordinate. Also, we have computed the maximum directivity as a function of (θ, φ) and their beamwidth in a similar way than in the 2D case.

In the earlier section we have addressed the performance of the designed configurations. We have examined the implications of the features of the set ups, such as directivity and
beamwidth. In the THz band the path loss due to spreading losses and molecular absorption becomes very significant, hence we stress out the need for overcoming this loss, and beam-forming is a suitable solution. By means of concentrating the power in a sharp beam, the range of links is enhanced and improved.
Chapter 3

Adaptive MIMO

3.1 Theory

The use of hundreds of radiating elements for every antennas has applications further than the beam-steering, fact that we highlight by introducing the concept of Adaptive MIMO. Adaptive MIMO is referred to the use of an antenna for propagating more than one power beam, for different applications that this technique may have.

3.1.1 Multi-User Environment

It is common in communication systems that there exists more than one users. These users will be located in positions that form various directions with respect to the transmitter. Hence, it is natural that this transmitter should communicate aiming the information to more than one angle. As Massive MIMO has been described so far this is impossible, so we need a new approach for the problem. We may consider the use of an antenna according to the following four schemes, as described in [1]:

- **Single User, Single Beam (SUSB):** there is a single user in the receiver side and the communication is conducted over a single path.

- **Single User, Multi Beam (SUMB):** the single user in the system is served by means of more than one path, either for diversity or multiplexing.

- **Multi User, Single Beam (MUSB):** there is more than one user and each of them is served with a single beam in the appropriate direction.
• Multi User, Multi Beam (MUMB): for each user there is one or more beams, allowing once again diversity or multiplexing.

From the previous schemes, the only one solved by Massive MIMO, understanding it as simply enhancing the directivity and hence the range of the link, is the first one. For the rest of them, we need a broader interpretation of this concept, such as the definition given for Adaptive MIMO. In figure 3.1 we see the four communication schemes described above. For the multi-path cases, the environment should provide with objects that produce scattering and reflections.

In parallel to the development of antennas capable of transmitting multiple beams we will present a multi-path channel model that will serve as a base for the proposed system. This model will consider the propagation features in the THz band, so the classical stochastical models that consider slow and fast fading should be revised to assess their validity.

In the introduction we presented the channel model for the communication in line-of-sight (LOS). In the multi-path model we will consider the contributions for the line-of-sight as well as non-line-of-sight (NLOS) directions. Consider significant path to be ray arriving at the antenna in a different direction, in a time-invariant narrowband channel. All NLOS paths are classified according to three categories, given in [51, 52, 53]:

**Reflections.** They occur when a ray is reflected over a surface in the specular direction (incident angle equals reflected angle). In this case the reflected power is a function of the material properties and the incident angle.

**Scattering.** The reflected ray does not propagate in the specular direction, but any other one, so the power degradation is greater than for the previous case. The surface characteristics determine the proportion of reflected and scattered power: their roughness, understood as the small height variations in the material. The scattering coefficient also depends on the incident and the scattered angle.

**Diffraction.** The rays are diffracted when they impact an edge of an object. The diffraction of the wave is a function of the edge and path features.
3.1. Theory

The impulsive response of the channel for this multi-ray model will be the sum of the contributions of each path, as described in [?]:

\[
H(\tau) = H_{\text{LOS}}\delta(\tau - \tau_{\text{LOS}}) + \sum_{p=1}^{N_{\text{ref}}} H_{\text{ref}}^{(p)}\delta(\tau - \tau_{\text{ref}}^{(p)})
+ \sum_{q=1}^{N_{\text{sca}}} H_{\text{sca}}^{(q)}\delta(\tau - \tau_{\text{sca}}^{(q)}) + \sum_{u=1}^{N_{\text{dif}}} H_{\text{dif}}^{(u)}\delta(\tau - \tau_{\text{dif}}^{(u)}),
\]

where \(H_{\{\text{ref, sca, dif}\}}\) correspond to the channel matrices for reflections, scattering and diffractions, respectively; \(\tau_{\{\text{ref, sca, dif}\}}\) are the delays of the paths; and \(N_{\{\text{ref, sca, dif}\}}\) are the number of resolvable paths for each case. The \(H\) matrices are composed of two terms, the propagation losses as in the LOS model and another coefficient that depends on the type of path: reflection, scattering or diffraction. It is worth mentioning that this model is built in the temporal domain, so in order to compute the attenuations we need to convert it to the frequency domain, which is easily done since we are assuming a narrowband time-invariant channel. There have been measurements related to this ray-tracing approach model, found in [54, 55]

3.1.2 Massive MIMO Subarrays

The idea on which Adaptive MIMO relies on consists of dividing the Massive MIMO array into different subsets taken from the total antenna array, and working as if each of them were an independent antenna. Hence, we may take consider an antenna and divide it in several subarrays, fed as according to our interests.

The main motivation that justifies the study of Adaptive MIMO over the previous configurations is its flexibility. For example, let us consider an array in 3D with elements placed along the \(x\), \(y\) and \(z\) axes in an imaginary cube layout, with dimensions \(10 \times 10 \times 10\) elements. We require to set up a link with that due to the channel characteristics demands a directivity \(D\) at the transmitter antenna. Then we may take a \(5 \times 5 \times 5\) subarray that satisfies the demanded directivity. In this antenna, there will be still be available seven subarrays as the one we just used, as shown schematically in figure 3.2, where we observe in red the used subarray in the cube-shaped antenna array. The rest of subarrays can be used for other communications that may have nothing to do with the first one. Also, we could suggest the use of the first subset to be of \(6 \times 6 \times 6\) elements, and adapt accordingly the remaining elements.
In summary, elements can be selected as it fits best for the needs of the particular application. On the contrary, what happened with Massive MIMO is that independently of the required directivity or specific demands of the link, all antenna elements were used to obtain a better link in a particular direction, which obviously is a very limited interpretation of the possibilities we have. In order to guarantee the success of the design, two aspects should be taken into account. On one side, the behaviour of the subarray as an independent structure, its directivity and other meaningful properties. On another side, the interaction of each subarray with the rest of them, since each one will introduce interferences over the others, maybe preventing or at least eroding the communication. This is why it is important to have a deep understanding of Massive MIMO, because every subset will behave as an antenna array and its response will be equivalent to those configurations.

However, the novelty with respect to the former section is the influence among subarrays. The problems related to interferences should be properly addressed and solved: this is the main challenge and difference for a successful communication using multiple beams. These interferences come from other beams. Although beamforming provides an enhanced directivity, it does not prevent from power radiating in other directions than the desired one. Hence, this power becomes an interference in case a receiver is listening to that particular direction. In order to prevent or at least control this situation, we require the characterization of the secondary lobes of a subarray. The secondary lobes are those beams different than the main one that have lower power. For example, a back lobe may be considered as a secondary lobe.

In our work we have studied diverse Massive MIMO configurations, which have been used as subsets of the total antenna in the case of the set ups for Adaptive MIMO.

### 3.2 Simulations

In the present chapter we will analyze several *Adaptive MIMO* structures. We recall that Adaptive MIMO is the technique consisting of selecting different subsets of elements in an antenna array with the aim of serving the needs of a particular user in a multiuser environment, either in transmission or reception. This procedure is a natural extension of Massive MIMO,
in the sense that it is necessary a high number of elements in order to make a selection such that it allows concentrating the power in a particular direction.

In this study we have conducted the following simulations in 2D and 3D:

<table>
<thead>
<tr>
<th>Dimension</th>
<th># Beams</th>
<th># Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>4-Beam</td>
<td>12×12, 15×15</td>
</tr>
<tr>
<td></td>
<td>9-Beam</td>
<td>15×15</td>
</tr>
<tr>
<td>3D</td>
<td>8-Beam</td>
<td>5×5×5, 6×6×6</td>
</tr>
<tr>
<td></td>
<td>12-Beam</td>
<td>6×6×5</td>
</tr>
</tbody>
</table>

Table 3.1: Adaptive MIMO configurations

The notation in table 3.1 is explained in the next lines. On one hand, the number of beams represents the number of element subsets that we will consider for a specific antenna, and it may be also understood in this case as the number of users to serve or the number of distinct directions from which a receiver can listen to transmissions. On another hand, we have specified the number of elements in each subset (12×12 in the first case, for example), so to obtain the total number of elements in an antenna array we need to multiply the second and third columns. In every transmission we will select only the number of elements designated by the third column.

It is worth noting that there exists a compromise between the number of beams and the number of elements associated to it: the interferences produced by other beams cannot be neglected. By increasing the number of elements in each subset the beamwidth of each beam is reduced, hence allowing the angular space for transmissions or receptions in new directions. To conclude, in this chapter, as in the previous one, we have performed simulations distinguishing between 2D and 3D arrays, and the environments connected to them.

### 3.2.1 2D Configurations

As a first approach to the problem of serving or receiving from multiple users, we will focus on the Massive MIMO solutions proposed for 2D-arrays. We recall that these arrays are capable of condensing the power varying both spherical coordinates (θ, ϕ), however, due to simulation limitations, we will study the behaviour for the horizontal plane with θ = π/2 and ϕ ∈ [0, 2π].

Given a Massive MIMO antenna, we should clone it as many times as beams we want. As it has been pointed out in the introduction, there is a link between the number of beams and the number of elements in each subset. With the aim of reducing the space occupied by
the antenna, in our design we have chosen to exploit the existing space between elements to locate other beams. This method is illustrated in latter subsections.

4-Beam Antenna Array

By means of a 4-Beam antenna we intend to give service to four different users with independent informations located in suitable directions. The reciprocal is also possible: we could set up a receiver to capture data from four separate angles. We show the antenna configuration in figure 3.2.1. Let us consider a Massive MIMO array with elements equally spaced $\frac{\lambda}{2}$, as suggested in the preceding chapter. Now we shift the mentioned array by $\frac{\lambda}{4}$ in the $x$ axis, building a new subset. We repeat this process for the $y$ axis and finally for both $x$ and $y$ at the same time.

The result is an antenna with four subsets of elements equally spaced $\frac{\lambda}{2}$, although the distances between them are smaller. All elements of each subset are denoted by a symbol:

- ○ Subset 1
- △ Subset 2
- × Subset 3
- ● Subset 4

The main benefit of applying this method is that the total antenna size is practically the same, because of the use of the intra-element spacing. A possible problem encountered by this solution consists of the impact of mutual coupling, since the separation between elements is very small. In our simulations we are using electrical point dipoles, which means that no such problem will be captured by our computations. However, the actual layout that we propose consists of stacking the different subsets in the $z$ axis, spaced by half a wavelength. By doing this, mutual coupling is avoided while the results for the simulations remain, even though these have been conducted in a 2D space.

Figure 3.3: 2D 4-Beam Array for Adaptive MIMO
3.2. Simulations

12×12 Antenna Array. Our first simulation consists of an antenna with 4 beams, each of them composed by a 12×12 array. In figures 3.4 and 3.5 we show two examples of the functioning of the proposed model. In the first case, the beams are pointed to the angles \( \varphi_1 = \frac{7\pi}{6}, \varphi_2 = \frac{8\pi}{6}, \varphi_3 = \frac{10\pi}{6} \) and \( \varphi_4 = \frac{11\pi}{6} \), while for the second the directions are \( \varphi_1 = \frac{\pi}{6}, \varphi_2 = \frac{2\pi}{6}, \varphi_3 = \frac{3\pi}{6} \) and \( \varphi_4 = \frac{7\pi}{6} \).

In order to guarantee the success of the proposed communications, we should characterize more specifically the parameters of the basic subset that shape a beam. If we fix as a condition that the main lobe of a beam shall be narrow enough to extinguish before any other propagation direction, then we ought to study the width of this lobe as a function of the angle \( \varphi \). Also, it is interesting to know the behaviour of the secondary lobe so as to estimate the potential interference power over different users. Each beam contributes in the leakage of power over directions that are not their specified one, so an estimation of the total interference is needed to measure the impact over the capacity. There is an equilibrium between the benefit obtained from increasing the number of beams and introducing a very high interference, which may actually harm the total capacity. This situation will be studied closely in latter sections, first by addressing the issue of the interference and then the interactions among beams.

15×15 Antenna Array. Now we repeat the simulations performed for a 4-beam antenna taking as a basic subset the 15×15 antenna array. The main benefit for this configuration as opposed to the previous one is the reduction in the beamwidth, which allows both a better...
discerning between directions and a better energy exploitation. In figure 3.6 we show the comparison between both beamwidths when pointing to different directions. We notice that for the $12 \times 12$ array, the main lobe ranges from $18^\circ$ to $25^\circ$, while for the $15 \times 15$ this interval is around $15^\circ$ to $20^\circ$. Although the greatest interference will be caused by the main lobe, secondary lobes should be taken into account too for computing the total interference.

![Figure 3.6: Main Lobe Beamwidth](image)

Also, we have explored the limits of angular separation between beams, as it is displayed in figures ?? and 3.7. In them we observe that even though there is enough angular separation in the chosen directions, the main lobes are not completely disjoint.

![Figure 3.7: 15x15 4-Beam Adaptive Array](image)

9-Beam Antenna Array

Once we have demonstrated the implementation of the 4-beam antenna array, we are ready to increase the complexity of our design by introducing new subsets to radiate in more directions. In particular, our suggestion is to reduce the spacing between subsets while keeping the separation between elements of the same subset, as shown in figure 3.8. In this figure we notice that the elements marked as $-$ are $\frac{\lambda}{2}$ away from each other, while the separation
3.2. Simulations

The only implementation that we have considered for this design is the one corresponding to the basic subset of $15 \times 15$ elements. This choice is a result of the beamwidth in the $12 \times 12$ array, because it makes no sense to have 9 beams available if the potential interferences are high.

Figure 3.9: $15 \times 15$ 9-Beam Adaptive Array

In figure 3.9 we show the results corresponding to two simulations in which we notice the capability of the antenna to distinguish between directions. Also, we notice an effect that has not been pointed out so far, such as the appearance of lobes with power comparable to the one in the desired angle. We observe that for the studied arrays, the problematic directions are $\varphi = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$. We should explore the compatibility between directions further than their angular proximity.
3.2.2 3D Configurations

In this section we will study how to extend 3D arrays for their use in Adaptive MIMO. In the earlier section we focused on the horizontal plane. Now this limitation is overcome and we have the freedom to aim the beam in the angles \((\theta, \phi)\). Following a similar reasoning than the one in the 2D case, in the design a key aspect will be the usage of the existing space between elements in order to place elements of new beams, and hence employ the space in a more efficient way.

8-Beam Antenna Array

This design is analogous to that for obtaining 4 beams in the 2D case. The procedure for developing it is explained in the next lines. Let us assume that we have a 3D Massive MIMO array with \(\frac{\lambda}{2}\) evenly spaced elements. Now we shift that array in the \(x\) axis direction, building a new one in that position. We repeat this method for \(y\), \(z\), \(\{x, y\}\), \(\{x, z\}\), \(\{y, z\}\) and \(\{x, y, z\}\). The result is an antenna with 8 element subsets, each of them with the same structure as the original Massive MIMO array, therefore with evenly spaced elements in \(\frac{\lambda}{2}\) in the three axes. In figure 3.10 we show the explained method with the subset \(-\) as starting point. All the subsets are represented by:

- Subset 1
- Subset 2
- Subset 3
- Subset 4
- Subset 5
- Subset 6
- Subset 7
- Subset 8

In the 2D configurations we pointed out that although for simulation purposes we developed the antenna by shifting the subarrays only \(\lambda/4\), in the actual design this will not be the case. Now we face the same situation: mutual coupling would have a great impact if the antenna had elements as close as presented in the figure, but due to computational limitations, this is the best solution to perform the the evaluation of the design. Our solution for the full implementation consists
of shifting the subarray enough to separate all the subsets at least half a wavelength. In this case, for the 8-beam configuration, the size of the total antenna will multiply by eight if compared to a single subset.

**5×5×5 Antenna Array.** In chapter 4 we presented the simulation of a 5×5×5 array, which is now used as the basic subset to build the 8-beam antenna with the instructions we described. In figure 3.11 we may observe the 8 beams pointing in the directions:

<table>
<thead>
<tr>
<th># Beam</th>
<th>$\varphi$</th>
<th>$\theta$</th>
<th># Beam</th>
<th>$\varphi$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$\frac{\pi}{3}$</td>
<td>5</td>
<td>$\pi$</td>
<td>$\frac{\pi}{3}$</td>
</tr>
<tr>
<td>2</td>
<td>$\frac{\pi}{4}$</td>
<td>$\frac{\pi}{2}$</td>
<td>6</td>
<td>$\frac{5\pi}{4}$</td>
<td>$\frac{\pi}{2}$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{\pi}{2}$</td>
<td>$\frac{2\pi}{3}$</td>
<td>7</td>
<td>$\frac{3\pi}{2}$</td>
<td>$\frac{2\pi}{3}$</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{3\pi}{4}$</td>
<td>$\frac{\pi}{2}$</td>
<td>8</td>
<td>$\frac{7\pi}{4}$</td>
<td>$\frac{\pi}{2}$</td>
</tr>
</tbody>
</table>

We have chosen these directions in order to make all beams clearly distinguishable, but a closer study will show the limits in the directions at which power beams do not influence each other. This will be conducted when we analyze the interferences.

Let us recall that red color represents a high magnitude, while blue a small one. It is worth mentioning that the figure represents the far-field, so in order to compute the diagram of radiated power we should square this graph. Despite the fact that lobes can be distinguished easily, as it was suggested in the previous section, it is interesting to characterize the beamwidth and the secondary lobes in order to predict interferences among various beams.

![Figure 3.11: 5×5×5 8-Beam Adaptive Array](image)

**6×6×6 Antenna Array.** Now we repeat the simulation for the case of taking every subset to be a 6×6×6 antenna. This time the beam will be considerably thinner, so the margin for distinguishing directions will improve. The process for building the antenna is the same as presented before. The figure 3.12 reflects the 8 beams aiming in the following directions:
Four of the beams are aiming at the horizontal plane, while the other four are pointing to an elevation angle of $\pi/3$, all of them easily distinguishable. If we look closer we notice the secondary lobes, presumably causing interferences. Since in the figure we represent the far-field, the conversion to power will lead to a better performance since by squaring the secondary lobes their normalized power will be lower.

We need to study the beamwidths for this and the previous model, which we present in the following figure, which represents the width of the main lobe when the $\varphi$ angle is modified along the horizontal plane, with $\theta = \pi/2$:

For the $5 \times 5 \times 5$ configuration, the beamwidth ranges around $50^\circ$, not allowing angular space for more than 6 beams in the same plane, while the use of a $6 \times 6 \times 6$ looses this limitation in ten degrees. The main difference with respect to the 2D configurations is that this beamwidth is effective in both angular directions: $\varphi, \theta$. In the planar arrays, although the beamwidth was thinner, in the vertical angle this beamwidth broadened.
3.2. Simulations

12-Beam Antenna Array

The last configuration of this chapter is a combination of others already introduced. It allows beamsteering up to 12 different directions. Due to computational limitations in the 3D environment, we will not reduce the separation between elements to $\frac{\lambda}{6}$, as we did in the design for the 9-beam 2D array. Instead, we will keep the minimum distance between elements to $\frac{\lambda}{4}$, in the way we demonstrate in figure 3.10. The construction of this model is based on shifting $\frac{\lambda}{4}$ the basic array in the axes directions $x$, $y$ and $z$ as we did in the earlier cases. In this design we generate two levels in the $z$ axis, to obtain the 12 subsets. Hence, the distances between elements in each subset are $\{\frac{\lambda}{2}, \frac{\lambda}{4}, \frac{3\lambda}{4}\}$ in the $\{x, y, z\}$ axes, respectively. In preceding chapters the arrays presented a $\frac{\lambda}{2}$ separation between elements. We need to study the impact of introducing a higher separation, since it translates into the presence of diffraction lobes, depending on the chosen angle for the beamsteering. Once more, we will also demonstrate the beamwidth and the secondary lobes. The list of subsets is the following:

- Subset 1 = Subset 4 = Subset 7 = Subset 10
- Subset 2 = Subset 5 = Subset 8 = Subset 11
- Subset 3 = Subset 6 = Subset 9 = Subset 12

Note that with the presence of 12 beams the interferences should be looked very closely. From the previous antennas we expect to have a reduced beamwidth that will allow allocating them while keeping the interferences under a certain threshold.

We suggest the proposed layout due to limitations in the computational capabilities, but the actual configuration will have elements separated enough to avoid mutual coupling, as mentioned earlier. The equilibrium of number of beams and number of elements relation is kept here,
since from the previous configurations we notice that there is angular space for other beams. In figure 3.15 we notice the 12 beams pointing in three vertical different angles: 4 at $\pi/3$, 4 at $\pi/2$ and 4 more at $2\pi/3$. The beamwidths for these lobes will take values close to previous 3D configurations, since the layout is very similar and the number of elements for every subset is in the same order. In the vertical array, the beam is narrowed since the electrical distance between elements is increased. The impact in the directivity is lightly appreciated, the only issue comes with the size increase that it causes. The remaining question is the same as for the rest of configurations: the influence of secondary lobes, addressed in the following section.

3.3 Performance Evaluation

3.3.1 Secondary Lobes

In this section we will analyze the impact of interferences produced when using different subarrays of an Adaptive MIMO antenna. We have studied the beamwidth of the main lobe, so now we will focus in the case of the secondary and back lobes, those that are not the principal one, and thus, have a lower maximum directivity (the back lobes may have the same power as the main lobe). These lobes will cause interferences in the directions that they point to.

As it occurred with the beamwidth of the main beam, the power of the secondary lobes depends on the direction at which it is aimed, so it is worth studying this dependence since
3.3. Performance Evaluation

the influence over the overall system will be greater or lower according to this magnitude.

In figure 3.16 we show the maximum interference level produced as a function of the direction of the main beam ($\varphi$ angle) for a $15 \times 15$ configuration. We observe a periodic behaviour similar as the one in the beamwidth. For the angle $\varphi = 0$ there is an angle at which the interference power has a level equal to the main beam (a back lobe in this case). This figure does not provide detail for the direction at which this second beam is aiming, it only gives a grasp on the interference power that we should expect when using this antenna array. In order to assess whether there is space for a beam, we should look at the particular angle at which we want to propagate, calculate the radiated power in that direction and evaluate this interference.

For the 3D case we have taken the $6 \times 6 \times 6$ configuration. Figure 3.17 reflects the power of the lobe with most directivity after the main one, in logarithmic scale. The smallest secondary lobe has a power of -15 dB with respect to the main lobe, which means that for that particular direction, all the lobes have a directivity in a level lower to that value. Again, the appearance of back lobes produces beams of power density equal to the main one.

As an example we will consider the level of interference that a subarray causes when radiating power in a particular direction. Let us consider the case for the $6 \times 6 \times 6$ pointing at $(\varphi, \theta) = \left(\frac{\pi}{4}, \frac{\pi}{2}\right)$. In figure 3.18 we show the directivity normalized by the maximum, at 0 dB. The maximum power other than in the main beam is around -15 dB, a value that corresponds to the one shown in the previous figure 3.17 for the given direction. We notice that the

Figure 3.17: Interference (Secondary Lobe)

Figure 3.18: Radiatio Pattern for a $6 \times 6 \times 6$ Array
interference is not critical in most directions, although it needs to be taken into account.

3.3.2 Capacity

Once we have characterized the interferences, we are ready to evaluate their impact over the system. According to Shannon’s formula, we have:

\[ C = \log_2 \left( 1 + \frac{S}{N + I} \right) \text{ [bits/s/Hz]} \]

where \( S \) is the received power, \( N \) the noise level at the receiver and \( I \) the interference power. Also, we may further decompose these terms in:

\[ S = P_T \cdot P_L \cdot D_T \cdot D_R, \quad I = S \cdot i_l \]

\( P_T \) is the transmitted power, \( P_L \) the path loss due to propagation and molecular absorption, \( D_T \) and \( D_R \) the directivities at transmitter and receiver and \( i_l \) is the interference level when compared to the maximum directivity of the subarray.

Let us assume that we have an Adaptive MIMO antenna with up to two different beams with directivities of \( D_T = 148 \) that correspond to a \( 15 \times 15 \) array, while the receiver antenna has \( D_R = 1 \). The path loss will be determined by the frequency of the transmission and the range of the link. The power magnitudes for the transmitted signal and received noise will be:

\[ P_T = 1 \text{ mW (0 dBm)} \]
\[ P_N = 10 \text{ pW (-80 dBm)} \]

We will compute the total capacity of the system by using one or both subarrays, understanding that in the case of using both there will be interference between them with a level of interference \( i_l \), because of the secondary lobes. For simplicity, we assume that this interference level is the same from the first subarray to the second and the second to the first.

\[ C_{1\text{sub}} = \log_2 \left( 1 + \frac{P_T P_L D_T}{P_N} \right) \]
\[ C_{2\text{sub}} = 2 \log_2 \left( 1 + \frac{P_T P_L D_T}{P_N + P_T P_L D_T i_l} \right) \]

We have conducted two evaluations for understanding the implications of interference, both using a subarray of \( 15 \times 15 \) elements. In the first one, the range of the link was \( d = 2 \text{ m} \) at
3.3. Performance Evaluation

A frequency of $f = 60\text{GHz}$. The blue and green graphs in figure 3.19 show that in case of using two $15 \times 15$ subarrays, we obtain a better total capacity with respect of only one subarray as long as the interference between the two subarrays stands below 0.04. This means that the directivity of a subset in the direction that the other one is aiming should not be greater than 4% of the maximum directivity of the maximum directivity $D_T = 148$. For the second one, the distance of the link is $d = 0.1\text{m}$ at a frequency $f = 3\text{THz}$. In the red and magenta graphs we observe that the capacity is equal at an interference level of 10%.

As the path loss increases, either due to the distance of the transmission or the frequency used, the interference becomes less significant. This means that an environment will be more favourable for Adaptive MIMO when the path loss becomes the limiting factor. Despite the fact that the interference levels computed for these systems are not too high, so they may be handled, it is true that the magnitude of the secondary lobes cannot be neglected when introducing a new beam in the communication.
3.4 Conclusions

In this chapter we have presented and studied a set of Adaptive MIMO configurations, understood as the application of Massive MIMO for the use of more than one beam in the communication. The main contributions that we have are summarized as follows:

- Antenna designs that enable the use of more than one power beam, with the objective of increasing the number of users served by a single antenna.
- Interference analysis of the power leaked by secondary lobes of the antennas.
- Capacity study under the influence of the interferences of other beams.

In the first section we proposed the use of 3D configurations formed by the 2D subarrays developed in the previous chapter. These 2D arrays were set up in layers and worked independently among them. We have pointed out the existing compromise between the number of beams and the number of elements in each subarray, due to interference restriction.

After this, we have extended Massive MIMO 3D arrays to become subarrays of our Adaptive MIMO 3D arrays, following a reasoning parallel to the one in the earlier section. Due to computational reasons, the conducted simulations do not correspond to the actual suggested implementation, since the placement of elements at close distances implies the effect of mutual coupling. However, the interferences and beamwidths remain unaltered for the simulations.

In the earlier section we have devoted our efforts to assess the performance of Adaptive MIMO focusing on its fundamental and most problematic difference with respect to Massive MIMO, the interferences. In particular, we have addressed the issue of secondary lobes, highlighting their importance when more than beam is used. Also, we have studied the effects of the interfering power over the total capacity of the system, which have proven to be significant although not overwhelming.

Finally, from this chapter we conclude that Adaptive MIMO overcomes some of the limitations that Massive MIMO presented, specially those related to enabling systems in a multiuser environment. Despite this fact, there are remaining issues that need to be solved, such as the interference problem and the power spectrum usage, which will be addressed in the next chapter.
Chapter 4

Multi-Rate MIMO

4.1 Theory

In the suggested antennas up to now, we have not mentioned the frequency spectrum and its use as a design parameter. Hence, we have implicitly assumed that the systems utilized a single frequency for the transmission of information. However, this is not a realistic premise, since the available spectrum in the THz band is very broad, as it has been mentioned. In this chapter we want to study the design of antennas working at different frequencies (multi-band) and its application to provide with a capacity adapted to the needs of every user (multi-rate).

4.1.1 Antenna Bandwidth Limitation

The radiating elements in an array constitute antennas by themselves. We need to consider their operation independently of the total antenna for the right performance of it. There are two main reasons why these elements will not be understood as “broadband”, this is, working at a frequency spectrum as broad as the THz band (0.06-10 THz). On one side, the designs are based on the electrical distance, and the separation between elements depends on this metric. When a significant variation with respect to the carrier or central frequency is produced, the results will not be as predicted by the modelling. On the other side, the antennas that work in a broad spectrum are more costly and complex, hence assuming that we may develop an antenna made of hundreds of these as basic element is not realistic.

The antenna bandwidth limitation is considered as a determining factor for the exploitation of the frequency spectrum, and thus, for providing different bit rates to the users according to their requirements.
4.1.2 Arrays with Diverse Antenna Lengths

In this part we outline a possible solution to the issues asserted in the former. In particular, our suggestion comprises the alteration of Adaptive MIMO techniques with the idea of making each subset work in a different frequency. By this approach, we solve satisfactorily the following:

- **Interferences:** One of the problems faced in Adaptive MIMO was the interferences among the beams of the various subarrays. Now, for subarrays transmitting in different frequency bands, this interference is avoided.

- **Element Complexity:** By reducing the spectrum over which elements are operational we allow their simplification, hence reducing their cost significantly.

- **Spectrum Usage:** The THz band is characterized by having a very wide frequency spectrum available for communications, with several transmission windows depending on the distance of the link. The idea of introducing diverse subsets with different frequencies will provide the fundamental basis for the proper exploitation of the whole spectrum.

Our multi-rate antenna will have various element subsets working in several frequencies, as a result, the spacing between elements will be placed according to this circumstance. For Massive and Adaptive MIMO the designs were fully characterized by the electrical length, this is, normalized by the wavelength. This made the designs independent from the frequency, at least at a geometrical level. However, the introduction of more than one frequency voids this statement, so every antenna will be designed with the aim of operating at a particular set of frequencies previously established, and modifying this set will translate into modifying the separation between elements other than the basic element separation.

4.1.3 Frequency Selection

Before immersing ourselves in the analysis of the proposed antennas, we consider adequate to study the frequency spectrum in which we are working, so as to make the most out of the resources it offers. In particular, we wish to select the appropriate frequencies that will determine the spacing between the elements of the built subarrays. In order to make the the right selection, the following factors need to be accounted for:

- **Sub-band of Interest:** The Terahertz band (0.06-10 THz) is very wide, so it will not be convenient to design an antenna that works over this whole spectrum, because the
4.1. Theory

variations in spacing among elements would be too high. Hence, it is necessary to focus on a part of it, a convenient sub-band.

- **Range of the Link**: There are significant differences in the behaviour of the channel depending on the distance that separates transmitter and receiver. We need to know the order of magnitude of this range and choose the frequencies that allow the communication in it.

- **Maximum Path Loss**: Closely related with the former parameter, the communication will be able to tolerate a maximum path loss due to propagation (spreading losses and molecular absorption). The frequencies that exceed this threshold for certain distance will not be suitable for the particular needs of the link.

- **Bandwidth**: Once we know the frequencies that satisfy the path loss limits, we should select the ones that allow the use of a given bandwidth under favourable conditions.

According to the previous specifications, we take the following values:

- Sub-band: 2-3 THz.
- Link Range: 1 m.
- Maximum Path Loss: 115 dB.
- Bandwidth: 50 GHz.

In figure 4.1 we observe the results for the frequency selection. There exist a total of nine channels suitable to accommodate a bandwidth of $B = 50$ GHz under the given premises, which are marked in cyan. In case that the available bandwidth was greater than $B$, we have selected the central frequency that minimized the standard deviation for the path loss.

![Figure 4.1: Frequency Selection for $B = 50$ GHz](image)
We repeat the procedure modifying the specifications as follows:

- Sub-band: 3-5 THz.
- Link Range: 1 m.
- Maximum Path Loss: 115 dB.
- Bandwidth: 70 GHz.

Figure 4.2 shows in cyan the frequencies chosen for the 11 usable channels. In red we observe the frequencies over the demanded threshold, while in green we have the band associated to the different channels. The graph in dark blue represents the path loss for non utilized frequencies under the threshold. We observe that the number of available channels is strictly related to the bandwidth that we provide for them: as we decrease this bandwidth, more channels can be allocated, but with less capacity.

4.2 Simulations

In this chapter we will design and analyze configurations named Multi-Rate. In the two previous chapters our efforts have been focused on incrementing the distance of links and providing transmitter and receiver with more than one power beam for communicating, without specifying explicitly the use of the frequency spectrum.

Our focus in this chapter consists of utilizing the already studied designs with the objective of exploiting the frequency spectrum at its maximum and by doing so solve the following problems:

- Interferences among users due to the use of the same carrier or central frequency.
- Inability to adapt the service offered to the demands of the users. We want to provide different speeds to them according to their needs.

In the table below we present the studied configurations:
4.2. Simulations

<table>
<thead>
<tr>
<th>2D Configurations</th>
<th>3D Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>12×12 (4 Frequencies)</td>
<td>6×6×6 (4 Frequencies)</td>
</tr>
<tr>
<td>15×15 (9 Frequencies)</td>
<td>6×6×6 (6 Frequencies)</td>
</tr>
</tbody>
</table>

Table 4.1: Multi-rate MIMO Configurations

Note that we will take the already developed configurations and extend them adequately.

4.2.1 2D Configurations

In this part we will study the use of 2D arrays that contain subarrays working at several frequencies in order to provide diverse capacities to users with different needs.

We will use the frequency selection provided in the description above to build the subarrays with the suitable separation among elements. Our approach consists of taking the configurations developed for Adaptive MIMO, in which there were various subarrays to shape every beam, and adapt these to every particular frequency. Hence, the result will be a multiband array with Massive MIMO subarrays in the chosen frequencies.

In the Adaptive MIMO chapter we were able to keep the antenna size by means of shifting every subarray. Due to the fact that the spacing between elements now are different for every frequency, this strategy is not satisfactory in this case. We suggest separating each array with enough space such that there are not elements of one subarray in the place occupied by another one. As it has been done so far, in this section we will analyze the case of a 2D environment. Thus, the separation among subarrays will be along the $x$ and $y$ axes.

As it occurred in the previous chapter, the theory to which the arrays are subject is equivalent to the Massive MIMO one. This means that the Array Factors are computed in the same way, and we only need to consider the electrical length of the subarrays to obtain the radiation pattern. With respect to interferences, the behaviour is qualitatively different to the former cases, since the use of multiple antennas reduces them to zero in case of using sufficient frequencies.

For the development of the actual configuration we propose to locate the subarrays in layers over the $z$ axis, as suggested in the previous chapter.
4-Frequency Antenna Array

We will place four subarrays in a two by two matrix as shown in figure 4.3. Each subarray has $12 \times 12$ elements spaced equally $\frac{1}{2}$ in the frequencies in the range from 2 to 3 THz associated with a bandwidth of 70 GHz, a path loss of less than 115 dB when the range of the link is 1 m:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Angle $\varphi$</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>2.11 THz</td>
<td>0</td>
</tr>
<tr>
<td>$f_2$</td>
<td>2.51 THz</td>
<td>$\frac{5\pi}{4}$</td>
</tr>
<tr>
<td>$f_3$</td>
<td>2.58 THz</td>
<td>$\frac{5\pi}{3}$</td>
</tr>
<tr>
<td>$f_4$</td>
<td>2.83 THz</td>
<td>$\frac{3\pi}{2}$</td>
</tr>
</tbody>
</table>

In the conducted simulation we have fed each antenna with the proper frequency taking the angles $\varphi$ shown in the table. In figure 4.4 we observe the different beams for every frequency. Note that the results consist of four beams with their corresponding secondary lobes. However, in this case interferences are not significant as long as the sent signal is kept with a bandwidth that does not invade the other channels. In principle, the capacity will be multiplied by the factor of the number of subarrays, but we should also take into account how the power is splitted among the subarrays in order to state this as a fact. Also, it is worth mentioning that for Multi-rate MIMO, once we have selected the frequencies and built the subarrays, we lose the flexibility that we had for Adaptive MIMO. In the previous chapter, the total antenna array was constructed using elements that radiated at the same frequency, so the selection of the subarray was conducted maybe for every communication. In this case the situation is different since the selection of frequencies limits the use of each subarray to the associated one. Hence, it is important to choose the proper configuration for the elements in the design process.
4.2. Simulations

9-Frequency Antenna Array

For this configuration we take 9 different frequencies that constitute a matrix with three columns and three rows with a total of $15 \times 15$ elements placed as given in figure 4.5.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Angle $\varphi$</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>2.11 THz</td>
<td>$\frac{\pi}{2}$</td>
</tr>
<tr>
<td>$f_2$</td>
<td>2.30 THz</td>
<td>$\frac{5\pi}{4}$</td>
</tr>
<tr>
<td>$f_3$</td>
<td>2.43 THz</td>
<td>$\frac{3\pi}{4}$</td>
</tr>
<tr>
<td>$f_4$</td>
<td>2.50 THz</td>
<td>$\frac{13\pi}{4}$</td>
</tr>
<tr>
<td>$f_5$</td>
<td>2.55 THz</td>
<td>$\frac{7\pi}{4}$</td>
</tr>
<tr>
<td>$f_6$</td>
<td>2.60 THz</td>
<td>$\frac{\pi}{4}$</td>
</tr>
<tr>
<td>$f_7$</td>
<td>2.73 THz</td>
<td>$\frac{3\pi}{4}$</td>
</tr>
<tr>
<td>$f_8$</td>
<td>2.82 THz</td>
<td>$\frac{2\pi}{3}$</td>
</tr>
<tr>
<td>$f_9$</td>
<td>2.92 THz</td>
<td>$\frac{\pi}{4}$</td>
</tr>
</tbody>
</table>

Figure 4.5: $15 \times 15$ 9-Frequency

Repeating the procedure shown above, we feed every subarray at the design frequencies. The conditions are the same as for the 4 frequencies, but we have relaxed the requirement for the bandwidth to be 50 GHz. The angles at which we aim each beam are listed with their associated design frequency in the table above. We have increased the number of elements for each subarray to demonstrate that the beams do not overlap. However, since we are working in a different frequency for each subarray, this is not required.

This configuration will lead to the ability to serve each user with a different capacity. As we have seen, for every frequency we have an associated channel, with a bandwidth given by the path loss limitation specified for each communication. So, this bandwidth will depend on the particular user, making it possible to adapt the modulation to the available spectrum. Also, if the requirements are such that one channel is insufficient for the demanded capacity, then more than one channel can be associated to a user, using a multicarrier scheme based on those that are already existing.

Figure 4.6: $15 \times 15$: Beams for each Frequency
Chapter 4. Multi-Rate MIMO

The simulations computed in previous chapters allow to save details over those presented in this part. We are already familiar with the beamwidth and the directivity of every subarray as a function of the angle at which we radiate, as well as their secondary lobes. The fact of working in different frequencies guarantees an independence among beams greater than the one provided in Adaptive MIMO: we can declare that the behaviour of the configuration is that of diverse Massive MIMO arrays that do not benefit nor are harmed from the presence of other subarrays. In the Performance Evaluation section we will study the capacity of these systems under different metrics.

4.2.2 3D Configurations

In the Adaptive MIMO chapter we used the strategy of slightly shifting the arrays to allow space for others and hence obtain different beams. However, given that the spacing between subarrays is now variable due to the utilization of more than one frequency, this procedure is not feasible in this scenario. There is also the concern over the proposed 3D configurations over the multipath propagation on their inside caused by the placing of the elements in a cubic disposition.

4.2.3 Surface Configuration

We have described two problems related with the layouts for the 3D antennas.

- Placement of multiple subarrays in a computationally feasible model.
- Placement of elements in order to minimize the path obstruction among them.

In order to solve this, we suggest to use an antenna configuration that we have not studied yet, which consists of placing the elements in the surface of an imaginary cube, following a λ/2 spacing among elements. It consists of 6 2D arrays, one in each face. The difference between this configuration and the previous ones resides in the fact that we have eliminated the interior elements.

For the current provided to each element in order to achieve beamforming, we will assume that this is the same as in the other 3D configurations. When we had a 3D array the feeding would be arranged by a phase difference that was related to the position in each of the axes x, y and z. Now we repeat the process, except that the interior positions do not have an element associated to the corresponding current.
4.2. Simulations

Regarding the Array Factor of this configuration, we notice that the loss in symmetry prevents us from obtaining a simple expression that reveals the radiation pattern in a product form. However, we may express it as a difference of two known Array Factors. Let us denote by $\mathbf{AF}_{3D,n}(\varphi, \theta)$ the factor for a 3D array with $n \times n \times n$ elements. Then, for a surface configuration with $n$ elements in its edge we have:

$$\mathbf{AF}_{\text{surface},n}(\varphi, \theta) = \mathbf{AF}_{3D,n}(\varphi, \theta) - \mathbf{AF}_{3D,n-2}(\varphi, \theta)$$

This is because we may interpret our empty cube as the difference between a configuration as those in Massive MIMO and that corresponding to a cube inside it. The total number of elements for this configuration is:

$$n^3 - (n - 2)^3 = 6n^2 - 12n + 8$$

With respect to directivity, beamwidth and secondary lobes, we will study the particular of a $6 \times 6 \times 6$ surface configuration, used after that for its use in multiple frequencies. Note that the number of elements of a surface grows as $\mathcal{O}(n^2)$, instead of cubically, which may allow to increase the size of $n$.

**Directivity.** The reduction in the number of elements with regard to other configurations will presumably diminish the directivity, since this value depends heavily on them. However, this is not the case. We have obtained the maximum directivity when varying the direction at which the main beam is pointing in the horizontal plane ($\theta = \pi/2$), and we notice that this metric remains very similar to the case of Massive MIMO, where all the interior elements were present. These results are shown in figure 4.7 for the $5 \times 5 \times$ and $6 \times 6 \times 6$ configurations.

![Figure 4.7: Directivity for Surface Array](image1)

![Figure 4.8: Beamwidth for Surface Array](image2)
**Beamwidth.** The angular broadening of the main lobe also depends on the direction at which we are aiming. It is calculated for the horizontal plane in figure 4.8.

**Secondary Lobes.** These lobes involve an energetic loss and provoke interferences by radiating in directions at which we should not, hence we should study them as we did in former sections. We have computed them and their behaviour is very close to that of the 3D configuration: in the case that back lobes appear, when aiming direction is aligned with the axes, then the secondary lobe has the same magnitude as the main lobe; as this direction is modified, the power of the secondary lobe is reduced. There are directions for which its power is as low as 2% for all directions other than the main beam.

### 4-Frequency Antenna Array

Considering our basic surface array configuration, we are prepared to build a multi-band array working in the following frequencies:

<table>
<thead>
<tr>
<th>$f_1$</th>
<th>2.11 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2$</td>
<td>2.30 THz</td>
</tr>
<tr>
<td>$f_3$</td>
<td>2.55 THz</td>
</tr>
<tr>
<td>$f_4$</td>
<td>2.92 THz</td>
</tr>
</tbody>
</table>

Each of these will have associated a subarray with elements equally spaced $\lambda/2$, being $\lambda$ the wavelength for every frequency. Hence, with the purpose of obtaining a computationally solvable antenna, we may place the subarrays one outside the other in decreasing frequency order, where the smallest one will have the highest frequency and minimum wavelength, to ascend to the largest cube which will contain the rest of them. We have simulated this array for the given frequencies, by feeding the proper element subset. In figure 4.9 we observe the result for the first two of them.

The method for the simulations consists of feeding the first subset for the first frequency, while keeping the current for the rest of them to zero, then apply the same algorithm for the

**Figure 4.9: Beams for $f_1$ and $f_2$**
second one, and so on. We observe the presence of secondary lobes, as we predicted for the configuration.

**6-Frequency Antenna Array**

We have conducted a simulation equivalent to the previous one for the case of considering a total of 6 frequencies. The method for placing them has been the same: cubes placed one inside the other in decreasing order of size, which is determined by the frequency that the cube is designed for.

<table>
<thead>
<tr>
<th>$f_1$</th>
<th>2.30 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2$</td>
<td>2.55 THz</td>
</tr>
<tr>
<td>$f_3$</td>
<td>2.73 THz</td>
</tr>
<tr>
<td>$f_4$</td>
<td>2.92 THz</td>
</tr>
<tr>
<td>$f_5$</td>
<td>3.21 THz</td>
</tr>
<tr>
<td>$f_6$</td>
<td>3.50 THz</td>
</tr>
</tbody>
</table>

The problem we have faced for solving this configuration lays on the spacing difference caused by the fact of using various frequencies. By increasing the ratio of the highest and lowest frequency we produce a denser meshing, difficulting the resolution. There is also a threshold for the minimum difference between two consecutive frequencies $f_n$, $f_{n+1}$, because in case any two are too close, the spacing between the corresponding cubes becomes negligible. These facts justify the impossibility to develop configurations with more frequencies. In figure 4.10 we observe the far-field for one of the simulated frequencies. The result is equivalent to the one given in the previous subsection, since the fact of increasing the number of subarrays should not modify the radiation pattern of the already existing ones, and as we notice from the equations for the Array Factor, it does not depend on the frequency.

### 4.3 Performance Evaluation

In this section we will conduct an analysis over the presented Multi-Rate MIMO configurations. In order to do this we will collect and use the results obtained for Massive and Adaptive MIMO configurations, since they will be useful to build insightful interpretations on the whole
spectrum of possibilities regarding the use of massive arrays. The most significant parameters to understand the performance of a Multi-rate MIMO system and compare it to another one are the following:

- Distance of communication.
- Frequency sub-band and number of channels.
- Available power and power spectrum density.
- Element configuration.

As stated in the Introduction of this work, there exist multiple environments in which communications in the THz Band may be feasible and convenient. Depending on the order of magnitude of the distance separating transmitter and receiver, it will be interesting to use a particular frequency sub-band or another one. Also, the number of channels could be a design parameter or a specification given as a need, so we should assess the advantages and drawbacks of making a broader or narrower use of the frequency spectrum and adapt the rest of the configuration to this demand. With respect to the power, there exist two limitations. On one side, it is possible that our system is limited by the total power available for a transmission, since an increase in power leads to a greater energy consumption and hence, a higher cost. On another side, it could occur that there is a limitation for the power spectrum density associated with that bandwidth, as it is the case for other frequency ranges. However, the THz Band is still unregulated. Finally, we should take into account the placement of the elements in the antennas, which determines the aspects of the radiation diagram.

With the objective of addressing a crosswise analysis on the most meaningful parameters, we will study three different scenarios according to the range of the proposed links: short range (up to 1m), medium range (up to 10m) and long range (up to 100m). For each scenario a capacity evaluation will be provided, as a function over the rest of specifications.

### 4.3.1 Short Range

The short range is lead to its use for nanocommunications or communication among devices. In these scenarios the maximum distance separating transmitter and receiver will be in the order of tens of centimeters. The size of the elements related to the communication (transceivers, antennas, etc) is a major concern in this environment. However, the propagation losses are not as restrictive as for the ranges described later on. Given that the antenna size depends on
4.3. Performance Evaluation

the frequency, as well as the losses, we have considered appropriate to utilize the higher part of the spectrum for short range links. In particular, we have chosen the range between 6 and 7 THz, assuming maximum losses of $P_L = 120$ dB at a distance of 1 m. For a bandwidth of $B = 50$ GHz we find up to 9 channels that could be used for our purposes.

Regarding the power assignment, we will assume an available power of $P_t = 1$ mW. Such power will be plugged either into a single subarray (1 frequency) or spread among different subarrays (9 frequencies) equally. From the previous premises and assuming that the path losses are equal for all the channels (approximately), a system has a capacity that depends on the number of channels as:

$$C = N \log_2 \left( 1 + \frac{P_t}{N} \cdot D_t \cdot P_L \right)$$

where $N$ is the number of channels, $P_t$ is the available transmitted power (split among the channels), $D_t$ is the directivity of the transmitting antenna, $P_L$ is the path loss and $N_0$ is the noise power, which we have considered to be $N_0 = 10$ pW.

![Figure 4.11: Capacity for Short-range Communication](image)

The remaining task before computing the capacity is to choose the element configuration. We have selected the 2D array that consists of $15 \times 15$ elements in each of the 9 subarrays placed
in layers in the $z$ axis. We have simulated and addressed its ability to direct up to 9 beams in the selected frequencies, each of them with a maximum directivity of 21.7 dB. In figure 4.11 we observe the results for the simulation.

We have plotted four graphs that represent the capacity of the system as a function of the link distance under different circumstances on the use of the antenna array. In the graph in cyan we have computed the capacity for an isotropic antenna. In dark blue it is represented the corresponding capacity for a $15 \times 15$ antenna to which we assign all the capacity. In the green and red lines we consider the use of the different subarrays allocated in distinct frequencies for the case of 9 available channels, begin the green graph a single channel and the red one the total capacity.

Observe that the separation between red and blue graphs narrows as we increase the distance range. From the previous statement we draw the following conclusions. If we are interested in a link that spans in a space of centimeters and there is a limit over the transmitted power, we should use as much bandwidth as possible. However, as we increase the range of the communication, it makes no difference splitting the power among the arrays or concentrating it in a single channel.

Regarding the interferences, we have noticed that the fact of associating every particular frequency to a subarray prevents them. In the Adaptive MIMO chapter we analyzed the impact that secondary lobes provoke over the capacity of the system. In this case, there is no diminishing in the capacity since the change in frequency produces the radiation patterns to be independent among them. This fact proves that a multi-band array may be an improvement with respect an array with only one wavelength, under the right circumstances. However, the increased complexity and the heavier use of the available spectrum are factors that should be considered when deciding between a single- or multi-band array.

### 4.3.2 Medium Range

This range could be used in an indoor scenario as a replacement of the current existing located in the microwave spectrum. In this environment the restrictions over the antenna size are not as tight as for the nanocommunications, but the propagation losses should be addressed with closer attention. We have chosen the band between 1 and 2 THz, with maximum losses of 130 dB, and obtained a total of 6 channels with a bandwidth of 50 GHz.

Due to propagation losses and with the aim of obtaining a significant capacity, we have increased the radiated power to $P_t = 10 \text{mW}$. In case of not owning this power magnitude, we should consider either reducing the range of the link or working at lower frequencies. We have
4.3. Performance Evaluation

considered the same magnitude for the noise power. Regarding the antenna configuration, we have chosen the surface array with $6 \times 6 \times 6$ elements, studied earlier in this chapter, with a directivity of $D = 19.4$ dB. The results for this simulation are shown in figure 4.12.

![Capacity Analysis for $P_t = 1$W, $f = 2$THz](image)

**Figure 4.12**: Capacity for Medium-range Communication

Once again we have assumed that the power loss is given by the worst case, which is $f = 2$ THz. The four graphs correspond to the uses described in the previous case. We notice the heavier reduction in capacity for case the sharing power between arrays as we increase the distance to the receiver. Also, it is obvious that the communication with an antenna that has no directivity is unfeasible, since the capacity is associated to this situation is negligible. The increase in power needed to compensate the directivity is equal to the factor given by it. Finally, we note that in case of having a limitation in power determined by the power density spectrum, it is always favourable to use multiple frequency subarrays, because they will only increase the capacity with respect to the already given by a single subarray.

4.3.3 Long Range

Finally, we want to analyze the scenario for a link of up to 100 m range. This type of communication will be possibly applied to backhaul links, for the information transmission among cells. The greatest problem faced in this environment are the propagation losses, while the antenna dimensions will be placed in a second plane (within reasonable limits). Hence,
the lowest part of the THz band is suitable for these links, also known as millimeter wave. In particular, due to the absence of molecular absorption peaks, for a threshold of $P_L = 130$ dB, we find that between 60 and 300 GHz the whole frequency band satisfies the limitations, so we have as many channels as we can place within this range.

The fact of dealing with this type of link allows to increase the transmitted power, since we need to overcome the propagation losses and the limits over the maximum power spectral density are not as strict. Nowadays there is still no regulation over the THz band. We have assumed a maximum power of $P_t = 100$mW, in an environment with noise power $N_0 = 10$pW.

Regarding the configuration for the simulation, we have chosen the 3D array with $6 \times 6 \times 6$ elements and 8 different beams. Although this configuration has not been studied for Multi-rate MIMO, its behaviour will be analogous to the given in the previous chapter. For each subarray the maximum directivity is $D = 20.3$ dB. In figure 4.13 we have computed the results for this simulation:

![Figure 4.13: Capacity for Long-range Communication](image)

There are some aspects worth noting from the figure. Once more, we have the four graphs already described that correspond to the possible uses of the given array. We also notice that the capacity in case of using multiple subarrays is significantly greater only if the link is several meters shorter than a hundred or if we increase the power in each subarray, assuming that the limitation over power is caused by the spectral density, instead of the energetic cost.
4.4 Conclusions

We have shown how a broader use of the spectrum can increase the capacity of the systems. Nevertheless, the applications of a multi-band array go further than that. We have mentioned the possibility of having users with different needs, and this may be an alternative use for antennas with elements of diverse lengths. To each frequency we associate a bandwidth and point the beam of the subarray to a user: in case of having enough capacity with this particular beam, the rest of them are still available. If this is not the situation, we may aim another beam to transmit to the same user. Let us consider \( C_{\text{channel}} \) the capacity of a single channel (that will depend on the frequency), then a user will have an available capacity \( N \cdot C_{\text{channel}} \), being \( N \) the number of frequencies associated to this user. If we compare this situation with the one in the previous chapters, we observe that for Adaptive and Massive MIMO this increase in capacity may only be achieved through modifying the transmitted power, which is not always possible.

In conclusion, we want to point out the similarities among the shown figures. This indicates the relation between transmitted power, frequency and distance. The capacity is independent of the radiation pattern, it is only influenced by directivity, which may be achieved by many different configurations and is closely influenced by the total size of the antenna and the number of elements. In order to capture the variations in performance over the various arrays, we need to recall the concepts of interference introduced in the Adaptive MIMO chapter.

4.4 Conclusions

The Terahertz Band is very wide, so we need to know the particular specifications of the application of the system that we are implementing in order to make the proper choice over the sub-band that we should use. Also, the information will be sent through multiple channels, given by the frequency band and the power losses limitations. In this chapter we have taken these factors to select the frequencies for the arrays that we simulated. The main contributions that we find aligned with this statement are:

- An antenna design based on placing the elements on the faces of a cube to reduce the impact of multi-path propagation in the interior elements.
- Analysis of the most adequate frequencies for the transmission of the information depending on the range of the link.
- Antenna designs with elements of multiple lengths, developed to enable the use of more than one frequency in the same antenna and hence make a more efficient use of the spectrum.
• Capacity analysis for systems that use more than one frequency, enhancing their benefits and limitations.

We have developed two types of configurations. On one side, we have those conducted in a 2D environment, for which we observe the different beams to be allocated in each frequency. For the 3D configurations, we found the challenge of solving the placement of multiple subarrays in a single model, since the fact that the spacing between elements varies depending on the frequency does not allow the use of the same method as that presented in Adaptive MIMO. This is the reason why we have developed and simulated a new configuration known as surface array, which consists of placing the elements over the surface of an imaginary hexaedron.

Finally, we have conducted a detailed analysis over the capacity for the different parameters. In this study we have addressed and characterized the main issues regarding multi-rate links, stating the differences with the other two MIMO implementations described in the work. In particular, we should understand Multi-rate MIMO as a paradigm for exploiting properly the available resources in the THz band and also offer the users different capacities according to their needs. We conclude that the sub-band, the distance and the power magnitude are three intimately related concepts that should be addressed in an unified way in order to converge the system to a solution for the requirements.
Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis we have studied the applications of beamforming in the context of THz band communications by means of large antenna arrays. In particular, this work has been structured following three different scenarios: Massive MIMO, Adaptive MIMO and Multi-Rate MIMO.

In the chapter devoted to Massive MIMO we have focused on demonstrating the benefits of applying directive antennas with the objective of increasing the range of a communication. The high path losses justify the need for these directive antennas. The directivity is achieved by means of large arrays: we have considered 2D and 3D arrays, which have been analyzed according to the symmetries found with linear arrays. The expressions for the Array Factor have enabled directing the power in the required direction.

The Adaptive MIMO chapter has addressed and solved some of the limitations found in the previous chapter. We have argued that the THz communications will need of technologies that allow multi-user scenarios, so transmitters should be capable of directing more than one power beam to different directions, which will be aimed as it is required. The main issue concerning this approach is the appearance of interferences. Those interferences have been studied and dimensioned, and from them we have deduced that the positioning of the users with respect to the transmitter is a key aspect when dealing with multiple beams communications. As we pointed out in the open issues, there is further research needed in this path to understand the impact of interferences.

In the last chapter we have discussed the importance of making an efficient use of the frequency spectrum by means of the use of antennas of diverse lengths in the same transmitter.
We have shown the beneficial impact of conducting an adequate selection over the frequencies according to the molecular absorption peaks and the associated bandwidths. We have analyzed the capacity of the systems under different premises for the utilized frequencies and distance ranges. We have seen that although the increase in capacity is not very significant, the use of multiple subarrays at different frequencies solves the issues related to interferences and it enhances the presence of multiple users.

5.2 Future Work

The Terahertz Band (0.06-10 THz) offers a very wide range of applications for wireless communications, both in the macroscale as well as for nanocommunications. However, due to the novelty of this technology, there are multiple challenges to be resolved before it becomes a communication paradigm. In this section we will point out those related to the use of MIMO techniques for beamforming.

We have introduced a system consisting of a transmitter or receiver with a large number of antenna elements, known as Massive MIMO. Such system is presented to solve the limitations in the communication produced by the propagation losses in this frequency range. The use of Massive MIMO entails the appearance of new issues that have not been addressed.

The impact of the correlation among elements caused by the radiation among them should be studied: this correlation will modify the channel matrix and consequently the radiation pattern of the antenna [56, 57, 58]. Furthermore, a Massive MIMO model considering these correlations and adapted to the use of hundreds of elements should be developed, since the channel estimation or coding might be different in this case.

The placement of the elements in a Massive MIMO array produces the propagation of the wave no to be in a free space environment, as it has been assumed when modeling the antennas as electric point dipoles. There is a need for a model that captures the fact that antenna elements have physical dimensions, and these will definitively produce undesired effects due to multi-path propagation. In the same path of reasoning, the feeding of these elements should be conducted concurrently to this multi-path model.

Moreover, the communications in the THz band will presumably take place in a multi-user environment. This has been our motivation for developing the systems named Adaptive MIMO. For them, we have suggested the use of subarrays to obtain different beams in diverse directions. However, it is still an open challenge what is the best algorithm to select those subarrays to satisfy the requirements of the communication as well as to efficiently utilize
5.2. Future Work

the available resources. In our work we have used a symmetric scheme in order to utilize the results from other sections, but this might not be the best approach.

Regarding the interferences, we have not considered that these might come from other transmitters. Although it is true that every transmitter should prevent or control interferences caused by their beams or subarrays among them, as we addressed in our work, reciprocally receivers need to take into account the interferences that their secondary lobes produce when aiming to other potential transmitters. A suggested solution for this problem consists of the combination of beamforming techniques along with interference cancelling, also given by the radiation pattern of an array. The proper feeding of the antennas is the key to solve this issue.

There are also open questions related to an efficient use of the spectrum and the assignation of resources to the users. A deeper study for the available bandwidths at each channel is needed for every particular application. This computation will be used to calculate the capacity, which is subject to other aspects in the communication such as modulation, channel estimation or coding. Once this work has been completed, then it is possible to allocate resources according to needs, by assigning frequencies depending on those. Finally, an important issue is the combination of the Adaptive and Multi-Rate MIMO results. With the aim of taking advantage of the benefits that each of them introduce in the communication scenario, an integrated understanding of both techniques should be developed, in a way which allows to transmit the information in more than one direction (multiple beams) by using several frequencies (multi-band) and enabling at the same time multiple capacities for different users (multi-rate).
Appendix A

COMSOL Simulation Environment

The simulation tool *COMSOL Multiphysics* [59] has been developed to evaluate various physical models, in particular those related to electromagnetism and wave propagation through the Radiofrequency Module [60]. The objective of this chapter is to provide the reader the material to become familiar with the instruments that COMSOL procures that support the completion of this work. In particular, we will describe and focus on the main elements in the simulation, as well as the most important parameters.

A.1 Architecture

A.1.1 Dimensions

COMSOL has several possible environments to perform simulations, from which we have chosen the 2D and 3D. Despite the fact that a communication system is embedded in a three-dimension context, the simplification obtained from reducing one dimension can be exploited in our benefit.

The 2D simulations are computationally much more efficient. This permits building structures that would be unsolvable in a three-dimensional space. Hence, we may study configurations in a simpler 2D environment and extend the results to the third dimension applying the suitable symmetry conditions. In our case, the use of 2D simulations will allow us to better understand the behaviour of the proposed models because in the plane results are more intuitive.

The simulations performed in a 3D environment will be conducted using a similar number of antenna elements (understanding this metric as an indicator of the complexity in the design)
than for the earlier mentioned 2D configurations. However, in the latter situation the total size of the antenna will be greater, since there is no third dimension available for locating layers of arrays.

A.1.2 Definitions

In the accomplishment of a complex model there is a need for tools that help to its manipulation in a simple manner. The possibility of selecting and defining subsets of it to associate a different physical behaviour to each part is very convenient. This operation has been conducted with the Perfectly Matched Layer, described later on, and the Far-field domain.

Furthermore, including certain variables in the Parameters section provides an easy way to modify the frequency, the separation between antenna elements and other important metrics in the design without introducing structural changes in it. We have developed designs that entirely rely on this parameters, in order to make them versatile in their application. For example, to modify the direction at which an array is aiming, we only need to change the two parameters that specify the polar angles.

A.1.3 Boundary Condition

The spatial limitation of the simulation should be treated adequately so as to make it not interfere in the results. Given that we will study the behaviour of the antennas either in transmission or reception but without establishing an actual link, we are interested in the radiation patterns of the designs and the far-field measurements. COMSOL allows fixing a free boundary condition for the resolution of the model, noted as Perfectly Matched Layer. In a circular or spherical shape, depending on the simulation dimension in which we are working, the PML has the task of regulating the physical limits of our model and making them behave as if they were infinite.

A.1.4 Antenna Configuration

The antennas that we will study are composed of hundreds of radiating elements. In fact, each of these elements constitutes itself an antenna that should be characterized and modeled so as to understand its impact in the whole model.

When a model is developed in a 2D space, it is already implicit that the radiating elements or antennas in it will be ideal, since all implementable antennas occupy a physical space.
A.2. Simulation Parameters

Additionally, in a 3D environment the fact of introducing an object with a size much smaller than the rest of the model complicates significantly the meshing (we will discuss this aspect later) and therefore the execution of the configuration. Provided that the scope of this work is not describing in detail each of the simulated elements in the arrays, but comprehending the interactions among them, we have considered convenient to assume the elements in the array to be ideal radiating points.

- **2D Simulations**: The element is a current point that travels through the XY plane perpendicularly. For practical purposes, this antenna radiates isotropically in the 2D environment. This power is given by the magnitude of the current that defines the element.

- **3D Simulations**: The element is an electric point dipole (ideal) with dipolar moment oriented in the z axis. The normalized diagram for the radiated power is shown in figure A.1. Its magnitude is obtained through the magnitude of the dipolar moment.

![Figure A.1: Dipole Radiation Pattern](image)

In the XY plane the dipole behaves as an isotropic antenna, which means that there is no difference between any propagation direction in terms of radiated power. However, this does not hold for the vertical angle \( \theta \), given by the YZ plane. In the diagram for this plane we observe that the radiated power depends on the angle as:

\[
P_{\text{vertical}}(\theta) = \sin^2 \theta
\]

This means that we will need to consider the effect of the electric dipole when modifying the elevation angle.

### A.2 Simulation Parameters

In this section we want to analyze the most influential parameters of the simulations, such as those related with the geometry, the materials in which the waves travel or the meshing. We will discuss how these parameters are given to COMSOL.
A.2.1 Geometry

The geometry of the models will be formed basically by two objects: the Perfectly Matched Layer and the radiating elements. As it has been pointed out, the PML is the boundary condition and will have a circular or spherical shape, with a width of $\frac{\lambda}{2}$ where $\lambda$ is the wavelength of the used frequency for the simulation.

The set of radiating elements constitutes the antenna, with its geometrical center coinciding with that of the PML. In order to build the antennas we will use the array object, which allows copying structures in a simple manner. For the case of a Massive MIMO antenna, let us consider a point: this point will be copied as many times as elements we need in the $x$ axis. Then, we will copy the result along the $y$ array to obtain a 2D array. Finally, if necessary, we will repeat the process for the $z$ axis. In Adaptive and Multi-rate MIMO, we take a Massive MIMO antenna as the starting structure and with the help of the array we can copy it to obtain different subsets that will allow diverse beams or frequencies. For building these structures we have used the Matlab software as explained in [61].

A.2.2 Materials

For the simulations we need to specify the materials through which the waves will travel, since the resolution of the model relies on these. Provided that we will have ideal antennas, we only require the material for the surrounding environment, in this case the air:

- Relative permeability: $\mu_r = 1$
- Relative permittivity: $\varepsilon_r = 1$
- Electrical conductivity: $\sigma = 0 \text{ [S/m]}$

A.2.3 Domain

This concept refers to the type of physical model that we demand COMSOL to associate to a part of the geometrical configuration: in time or frequency. Taking into account that we are interested in the behaviour of the antennas for one or several specific frequencies, we will use this domain for our simulations. Also, solving in frequency allows to compute the far-field domain and is requires less time to converge. Regarding Multi-rate MIMO, we will need more than one simulation since for every frequency there will be independent solutions.
A.2. Simulation Parameters

A.2.4 Meshing

The meshing of the system represents the set of points in which the model will be solved. There is a balance between the density of the meshing, the accuracy of the solution and the resolution time. In our model we have taken the following values for both 2D and 3D simulations:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum element size</td>
<td>( \lambda/5 )</td>
</tr>
<tr>
<td>Minimum element size</td>
<td>( \lambda/10 )</td>
</tr>
<tr>
<td>Maximum element growth rate</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table A.1: Meshing parameters

The parameter \( \lambda \) is the wavelength at which we are working. In case that there is more than one frequency that we want to simulate, we have taken \( \lambda \) to be the largest wavelength due to computational limitations. For the 3D simulations we have used a free tetrahedral meshing for the the domains, combined with a swept. These terms are related to the way in which COMSOL constitutes the set of points for the solution.

A.2.5 Study

The Study is the type of resolution that COMSOL should run. We note that this specification is closely related to the physical properties (domain) that we have provided for the model. Since the model has been associated with electromagnetic waves in the frequency domain, the resolution is also in this domain. In our case we have combined two types of study: Frequency Domain and Parametric Sweep. Through the first one we particularize the frequency for the resolution, while the second one is addressed to list a set of parameters and modify them along with resolving for each specific case. This allows to conduct multiple studies at various frequencies or aim the main beam at the direction we require.

Results

Once we have set and executed the simulation, we demand to analyze the results. These come in many various formats, so it is interesting to present those who will be meaningful in our work. We describe the two most important ones.
**Polar Plot 2D.** In this type of diagram we show in polar coordinates the results for certain magnitude in the adequate plane, for which we may specify both position and inclination. In particular, we have used it extensively for obtaining the Far-field (normalized electric field) in the case of 2D configurations, because it provides easy visualization of the beams in each direction.

**3D Plot.** In this representation we can include multiple results. For example, we may calculate the electric field for a set of planes in the physical model. Its graphical appearance can be rotated as it is required. In our case, we have utilized it for obtaining the radiation pattern (normalized electric field) of the antenna at hand. Given the results for the Far-field, we have gathered the magnitude of the different lobes propagating in the whole space. This diagram has been the base of all further calculations.

**Export.** The results from COMSOL should be manipulated to analyze and comprehend their implications. This is the reason behind the action of exporting them to other software (such as Matlab) in order to adapt them and extract the metrics for interpretation. From the far-field measurements we can obtain values for the directivity, beamwidth or secondary lobes.
Bibliography


