Mastering Spatial Resources

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Mastering Spatial Resources

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"If you shut your door to all errors truth will be shut out".
Rabindranath Tagore

Contents

Introduction

Wireless communications have always been fascinating to me as it involves both engineering, with the study of complex systems, and physics, with the understanding of wave propagation based on the science of electromagnetism. I therefore graduated in 2005 from the University of Nantes with a master degree in Electrical Engineering (specialty in telecommunications) and decided to go further with a PhD from the same University conducted at the IETR research institute in Nantes (formerly IREENA). My topic was related to antennas dedicated to MIMO systems and gave me the opportunity to gain knowledge about propagation channel in addition to the design of radiating structures. After my 3-year PhD in Nantes, I continued this work to some extent during my two-year position at BKBIET engineering college in India. I extensively taught during these two years that have been a rich experience on both personal and professional levels. In January 2011, I joined Telecom ParisTech in Paris for a 19-month post-doc position during which I worked on metamaterials and had also the opportunity to continue on MIMO antenna design. About 4 years after my PhD defense, in September 2012, I joined Sorbonne Université, formerly University of Pierre and Marie Curie, as associate professor.

This HDR thesis summarizes the professional activities I have conducted this last decade, both before and after I joined Sorbonne. This document is organized into four chapters as follows. The first chapter is my resume, including the list of PhD students I have co-supervized and the past and on-going projects I participated in. The second chapter introduces my research activities, presented into four main scientific themes. This chapter also introduces the people and the fundings involved in this research. The third chapter briefly summarizes the teaching I have done since I joined Sorbonne University and the last chapter presents the research project I intend to carry on for the coming years.

Note relative aux modalités de rédaction du mémoire d'habilitation à diriger des recherches à Sorbonne Université : *selon les UFR, votre mémoire d'habilitation, synthèse et perspectives de vos travaux d'environ 50 pages (hors les articles joints), en français ou en anglais, peut être ou pas déjà rédigé lorsque vous soumettez votre pré-dossier à la CTH.* *http://www.sciences.sorbonne-universite.fr/fr/recherche/hdr.html*

Chapter 1

CV

1.1 Academic Qualifications

2005 – 2008	**Doctorate of Philosophy (PhD) in Electronics and Telecommunications** University of Nantes, IETR laboratory (formerly IREENA) **Supervisor:** Serge Toutain, **co-supervisors:** Stéphane Avrillon and Yann Mahé Defended on 14 November 2008
2005	**Master of Research in Electrical Engineering** Polytechnique Nantes, University of Nantes
2005	**Master of Technology in Electrical Engineering (i.e., Engineer degree)** Polytechnique Nantes, University of Nantes

1.2 Positions Held

2012 – *now*	**Associate Professor, CNU section 63** Sorbonne Université (ex-University of Pierre and Marie Curie – Paris VI) Research at the Laboratory of Electronics and Electromagnetism (L2E)
2011 – 2012 *(19 months)*	**Post-doctorate** Telecom ParisTech, Paris
2009 – 2010 *(2 years)*	**Associate Professor** BKBIET Engineering College, Pilani, India
*Dec.*2008 *1 month*	**Research engineer** University of Nantes IETR laboratory (formerly IREENA)

1.3 PhD Student Supervision

1. **Michael Odhiambo**
   "Spatial Data Focusing"
   PhD started in October 2018
   Supervision rate: 80%
   Funding: ANR JCJC GEOHYPE
   Co-supervisors: Philippe De Doncker (ULB)

2. **Lyu Pengfei**
"Millimeter-wave indoor localization"
PhD started in April 2017
Supervision rate: 70%
Funding: Grant from China Scholarship Council (CSC)
Co-supervisors: Zhuoxiang Ren (L2E) and Aziz Benlarbi-Delaï (L2E)

3. **Thomas Van Der Vorst**
"Uncertainty Estimation in AoA-based Localization using Polynomial Chaos Expansion"
PhD started in September 2016
Supervision rate: 20%
Co-supervisors: Philippe De Doncker (ULB) and Aziz Benlarbi-Delaï (L2E)
Funding: Grant from FNRS, Belgium

4. **Duccio Delfini**
"Development of multipixel heterodyne imaging arrays for future space mission"
PhD started in October 2015
Supervision rate: 30%
Funding: CNES project
Co-supervisors: Martina Wiedner (LERMA) and Massimiliano Casaletti (L2E)

5. **Qiang Zhang**
"Antenna design dedicated to Body Area Networks (BAN)"
PhD started in October 2015
Supervision rate: 40%
Funding: Grant from EDITE doctoral school from Paris
Co-supervisors: Massimiliano Casaletti (L2E), Philippe De Doncker (ULB), and Aziz Benlarbi-Delaï (L2E)

6. **Halim Tannous**
"Interactive and Connected Rehabilitation Systems for E-Health"
PhD started in September 2015
Supervision rate: 10%
Funding: E-BIOMED - Sorbonne Universités, UTC Compiègne
Co-supervisors: Dan Istrate (UTC), Tien Tuan (UTC), and Aziz Benlarbi-Delaï (L2E)

7. **Ahmed Abudabousa**
"60 GHz Indoor Localization using Interferometry-based Time Difference of Arrival"
Defended on 17th April 2018
Supervision rate: 50%
Co-supervisors: Aziz Benlarbi-Delaï (L2E)
Funding: ERASMUS MUNDUS: Phoenix program
Current position: Associate professor at Islamic University of Gaza, Palestine

8. **Shrikanth Reddy**
"Design, Analysis, and Characterization of Body Centric Ultra Wideband (UWB) Antennas for On–Body/Off–Body Medical data acquisition and transmission"
Supervision during a 5-month visit at L2E in 2015
Supervision rate: 14%
Co-supervisors: Jayanta Mukherjee (IIT Bombay)
Funding: Grant from IIT Bombay, India
Current position: Assistant Professor at IIT Mandi, India

9. **Solofo Razafimahatratra**
"Propagation and communication strategies for Body Area Networks (BAN) at 60 GHz"
Defended on 14th November 2017
Supervision rate: 70%
Supervisors: Aziz Benlarbi-Delaï (L2E) and Philippe De Doncker (ULB)
Funding: Grant from EDITE doctoral school from Paris
Current position: Post-doc at ESPCI engineering college, Paris

10. **Fabien Defrance**
"Instrumentation of a Terahertz heterodyne receiver"
Defended on 14th December 2015
Supervision rate: 20%
Co-supervisors: Martina Wiedner (LERMA) and Massimiliano Casaletti (L2E)
Funding: CNES project
Current position: Post-doc at JPL, NASA, USA

11. **Théodoros Mavridis**
"Channel modeling for 60 GHz Body Area Networks"
Defended on 24th February 2015
Supervision rate: 20%
Co-supervisors: Philippe De Doncker (ULB) and Aziz Benlarbi-Delaï (L2E)
Funding: Grant from FNRS, Belgium
Current position: Expert at the European Patent Office in Den Haag, Holland

12. **Ahmadreza Jafari**
"New TDOA-based localization method for High Data Rate systems"
Defended on 24th February 2015
Supervision rate: 40%
Co-supervisors: Aziz Benlarbi-Delaï (L2E) and Philippe De Doncker (ULB)
Funding: Grant from EDITE doctoral school from Paris
Current position: Engineer at Renault, R&D department

1.4 Post-doc Supervision

1. **Ting Zhang**
"Indoor localization to detect emergency situations for elderly people"
October 2015 - September 2016 (1 year)
Funding: E-BIOMED - Sorbonne Universités
Current position: Associate Professor at Zhejiang University, China

2. **Zhongkun Ma**
"On-body antenna behavior and characterization for Body Area Networks"
June 2014 - May 2015 (1 year)
Funding: SMART LabEx: SMART-BAN project
Current position: Engineer at Tomtom, Eindhoven, Holland (RF antenna design)

1.5 Prizes and Achievements

2016	ANR JCJC: young researcher grant (225 k€ for the GEOHYPE project)
2014	Research allowance (from Sorbonne University)
2013	Labex grant (300 k€ for the SMART-BAN project)
2005	Bouygues Telecom *"Innovation prize"*

1.6 On-going and Completed Projects

1. **Indo-French project: NOVIS60**
   Participation as project Leader
   Funding granted, to be started in June 2018 (3 years, 200 k€)
   Funding Agency: Indo-French research Agency (CEFIPRA)
   Partners: IIT Bombay

2. **ANR JCJC: GEOHYPE**
   Participation as project Leader
   On-going project, started in November 2016 (4 years, 225 k€)
   Funding Agency: French National Research Agency (ANR)
   Partners: Université Libre de Bruxelles (ULB)

3. **Detection of emergency situations for elderly**
   Participation as project co-Leader with Prof. Dan Istrate and Dr. Guido Valerio
   October 2015 - September 2016 (1 year, 65 k€)
   Funding Agency: E-BIOMED program from the Health Engineering Institute (IUIS), Sorbonne Universités
   Partners: University of Technology of Compiègne (UTC)

4. **SMART-BAN: "Self-organizing, Mobility Aware, Reliable and Timely Body-Area-Networks"**
   Participation as project Leader
   September 2013 - August 2017 (4 years, 300 k€)
   Funding Agency: SMART LabEx from the French National Research Agency
   Partners: L2E (UPMC), LIP6 (UPMC), LTCI (Telecom ParisTech)

5. **e-patient: "Connected Patient – Post-Surgery Monitoring at Home"**
   Participation as project Leader
   March 2015- February 2016 (1 year, 10 k€)
   Funding Agency: Health Engineering Institute (IUIS), Sorbonne Universités
   Partners: L2E (Sorbonne), LIP6 (Sorbonne), Pitié Salpêtrière Hosptial

6. **MIMICRA: "Metamaterial Inspired Microwave Conformal Radar Antenna"**
   Completed in August 2014 (3 years)
   Funding Agency: DGA-DSTL from EDA (European Defence Agency)
   Partners: BAE Systems, Dassault Aviation, EADS-IW, MBDA, Oxford University, Queen Mary College, Telecom ParisTech, Thales Systèmes Aéroportés, Université Paris-Sud (IEF)

7. **PUMA: "Directive Antennas for High-Data Rate Wireless Communications at 40 GHz"**
   Completed in 2011 (3 years)

Funding Agency: French state - Fond Unique Interministériel (Inter-Minister Funding)
Partners: BluWan, Luceor, Prism, Telecom ParisTech, Thales, VectraWave, Wizeo

8. **Ultra Low Profile Absorbers for Space Applications**
   Completed in 2014 (10 months)
   Funding Agency: French Space Agency (CNES)
   Partners: CNES, Telecom ParisTech

9. **AIS: "Compact Antennas for Automatic Identification Systems"**
   Completed in January 2012 (1 year)
   Funding Agency: Thales
   Partners: CNES, Telecom ParisTech, Thales Systèmes Aéroportés

10. **MILES-MATTADOR: "Material, Technology, Processing, and Architecture, for Optics and Electronics Systems and Devices used in Communications"**
    Completed in December 2009 (3 years)
    Funding Agency: Pays de la Loire (French Region)
    Partners: IMN, IRCCyN, IREENA, LAUM, LGMPA, LINA, LSO, UCO2M

11. **Techim@ge: "Innovative Technologies for High Data Rate Local Area Networks"**
    Completed in February 2009 (2 years)
    Funding Agency: French state - Fond Unique Interministériel (Inter-Minister Funding)
    Partners: Acome, BBS One, ENSAAT, France Telecom, IETR, IREENA, LEA, Siradel, Telecom Bretagne, Thomson

1.7 Other Scientific Activities

1.7.1 Conference and workshops-related activities

- **TPC Member, local committee member, and Dissemination Chair of EUCAP 2017** (*11th European Conference on Antennas and Propagation*), Paris, France
- **TPC member of IEEE PIMRC 2018**, Bologna, Italy
- **Session chairman** at:
  - *IEEE Antennas and Propagation Symposium*, 2014, Memphis, USA
  - *European Conference on Antennas and Propagation* EUCAP 2017, Paris, France
- **Member of the technical committee** of the *International Conference on Communication Systems (ICCS)*, Pilani, India
- **Organizing Committee Member of GreenBAN 2014** (*International Workshop on Green Solutions for Body Area Networks 2014*), Paris, France, http://www.greenban2014.upmc.fr
- **Organizing Committee Member of IoT workshop**, Issy-les-Moulineaux, France, Nov, 2016, http://www.federation-electronique.upmc.fr/fr/manifestations-passees/er-colloque-de-la-federation-d-electronique.html

- **Local Organizing Committee Member of META** (*3^d International Conference on Metamaterials, Photonic Crystals and Plasmonics*) and **AES** (*1st Advanced Electromagnetics Symposium*), April 2012, Paris, France

1.7.2 Local positions

- **Elected member** of the *Scientific Council of the Engineering Department of Sorbonne University*, Paris, France
- **Elected member** of the *Laboratory Council of the L2E Research Institute*, Paris, France
- **Head of P-SYS group** (People and Communicating Systems) of the *L2E Research Institute*, Paris, France

1.7.3 Reviewing activities

- **Scientific reviewer for French Research Agency (ANR)**
- **Scientific reviewer for CIFRE PhD grant** (for PhD co-supervised with Industry)
- **Reviewer for the following journals:**

  IEEE Transaction on Antennas and Propagation

  IEEE Antennas and Wireless Propagation Letters

  IEEE Transactions on Vehicular Technology

  International Journal of Microwave and Wireless Technologies

  Advanced Electromagnetics (AEM)

  Journal of Applied Physics

- **Reviewer for the following international conferences:**

  European Conference on Antennas and Propagation (EuCAP)

  International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)

1.7.4 Memberships

- IEEE member
- COST Action CA15104 IRACON: member and contact person for Sorbonne University
- Member of the E-peer review scientific committee, http://www.epeer-review.com

1.7.5 Supervision and PhD jury

- **Involvement in PhD jury:**
  - 2 at Telecom ParisTech, Paris, France
    - Lana Damaj, “Antenne versatile intriquée”, 2013

    * Thanh Nga Mai, “Conception d’un système antennaire compact reconfigurable en fréquence dédié aux applications LTE”, 2014
  - 1 at ESYCOM, University Paris-Est Marne-la-Vallée, France
    * Maurício Henrique Bezerr Cardoso, “Modélisation de la propagation des ondes électromagnétiques près du sol : application aux réseaux sans fil”, 2017
  - 1 at Telecom Paris Sud, Evry, France
    * Nissem Selmene, “Etude et Développement de Capteurs Tactiles Flexibles à Détection Harmonique vers la Fonctionnalisation Sensitive des Surfaces”, 2016
  - 1 at University of Sienna, Italy
    * Santi Concetto Pavone, “Analysis and Design of Bessel beam and EM pulse launchers”, 2015
  - 1 at IETR, University of Rennes I, France
    * Carole Leduc, “Réseaux corporels sans fil en ondes millimétriques : antenne, propagation et interaction avec le corps”, 2015

- **Involvement in mid-term PhD jury:**

  7 at Telecom ParisTech, Paris, France

  1 at IETR, University of Rennes I, Nantes, France

  1 at ESYCOM, University Paris-Est Marne-la-Vallée, France

- **Master students supervision** since my position at Sorbonne University (Sept. 2012):

  8 Second year students (3 to 6 months internships)

  8 First-year student (2 to 3 months internships)

Chapter 2

Summary of past research activities

IN THIS CHAPTER are summarised the research activities I have been conducting since the beginning of my PhD in November 2005. Prior to that, we can cite the work I have done during my 7-month master internship at Bouygues Telecom that dealt with the design of a 23-GHz planar antenna array for microwave links between base stations in urban environments [1, 2]. The first section of this chapter introduces the scientific activities organized into four research themes. Selected publications are cited from the literature for each theme's introduction, and from papers I have (co-)authored for the work I have conducted (mostly the journal papers, for an exhaustive bibliography regarding this work, see my list of publications in appendix 4.5). The remaining sections deal with extra activities that are not purely science-oriented such as funding, resources, etc.

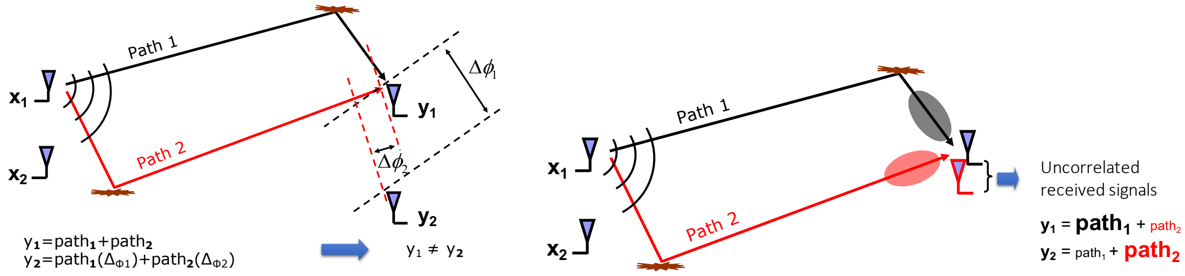
2.1 Research themes

2.1.1 Antennas for MIMO systems

Multiple-Input Multiple-Output (MIMO) systems use multiple antennas at both the transmitter and the receiver in order to increase the data-rate or the robustness of wireless links by using spatial resources [3]. In indoor or urban areas, complex propagation phenomena occur such as reflection, diffraction, and refraction, that create a multipath environment which is usually harmful to wireless communications. MIMO systems mitigate or even exploit these multipaths to improve performance without requiring additional frequency or time resources. The only additional feature MIMO systems require are multiple antennas, which consequently introduces more constraint on the front-end and the signal processing. Diversity-based MIMO techniques mitigate fading effects and therefore increase the average signal-to-noise ratio while spatial multiplexing exploit the multipaths occurring in the environment to create spatially orthogonal parallel communication channels in order to increase the data rate. When it was first proposed in 1993 and experimentally developed in Bell laboratories in 1998, the approach of spatial multiplexing triggered a great enthusiasm for MIMO systems, as it was seen as a promising solutions to increase wireless communication throughputs by taking advantage of multipath, that are usually considered harmful.

Concept of radiation pattern diversity:

Regardless the MIMO techniques under consideration, the performance largely depends on the correlation between the signal transmitted or received by the multiple antenna systems. To maximize the channel capacity, this correlation must be as low as possible and spatial diversity is commonly used to do so (see figure 2.1a). However, this requires a distance between antennas of less than 0.5λ (where λ it the wavelength at the carrier frequency) up to several λ depending on which kind of environment is considered. This is not always compatible with the limited volume available on a wireless terminal. That is why other kinds of diversity such as radiation pattern diversity are also investigated (see figure 2.1b). By using antennas with different radiation patterns in terms of amplitude, polarization, and/or phase, it is possible to reduce the size of the multiple antenna system while keeping a low correlation between signals.



(a) Spatial diversity

(b) Radiation pattern diversity (amplitude)

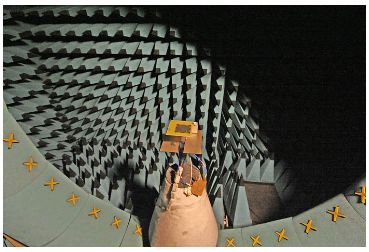
Figure 2.1: Example of antenna diversity at the receiver.

Achievements:

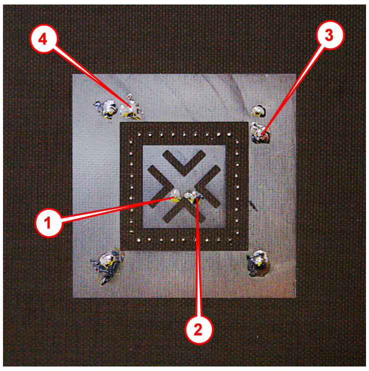
During my PhD (2005-2008) and my post-doc at Telecom Paristech (2011-2012), we proposed several antenna systems well suited for MIMO applications [4, 5, 6, 7, 8, 9]. For instance, to achieve pattern diversity, we proposed different solutions based on multimode (e.g., figure 2.2a) and intricated (e.g., figure 2.2b) antennas, capable of producing uncorrelated radiation patterns while being collocated. We also proposed radiation pattern reconfigurable antennas (e.g., figure 2.2c) that can either adjust their radiation characteristics with respect to the channel variation (since the MIMO performance highly depends on the channel), or be used as a virtual multiple antenna system to decrease the complexity and the size of MIMO hardware. The antenna design of such solutions requires insights of the MIMO propagation channel and therefore requires a multidisciplinary approach to be done efficiently. To assess the performance of the proposed antenna systems, we developed a measurements setup in order to measure the MIMO channel propagation matrix from which the channel capacity was determined. To obtain more insights regarding the influence of radiation pattern on the performance, we developed a stochastic ray-tracing tool to observe directly the influence on the channel capacity of the Angle-Of-Arrival and Angle-Of-Departure distributions as well as the polarization of transmitted and received waves (including the depolarization in the channel).

2.1.2 Metamaterials to manipulate electromagnetic wave radiation

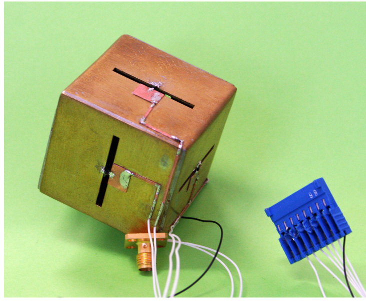
Metamaterials are artificial composites that are engineered to exhibit properties that are not otherwise found in the nature. They are usually 2D or 3D lattices of periodic metallic or dielectric structures whose spatial period is small with respect to the wavelength. In this context, we have especially investigated planar High Impedance Surfaces (HIS [10]) that can act as Artificial Magnetic Conductors (AMC). Using those, we developed wideband antennas with reduced thicknesses as well as planar and light electromagnetic absorbers for space applications.



(a) 3D measurement of a multimode antenna using a frequency convergence concept [7]



(b) Four collocated antennas with low mutual coupling [6]



(c) Pattern reconfigurable antenna [5]

Figure 2.2: Example of prototypes of MIMO antenna systems.

HIS concept:

The interesting property that triggered research in this area is the ability for a HIS to reflect incident waves without a π phase shift, as classically introduced by electric conductor-based reflectors. Using this, omnidirectional antennas such as dipoles or Archimedean spirals for instance, can benefit from such HIS reflectors in order to achieve a low profile structure, as shown in figure 2.3.

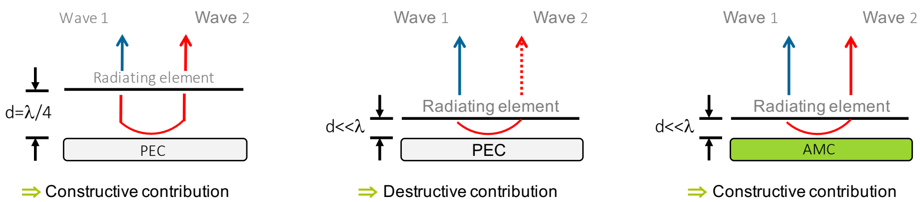


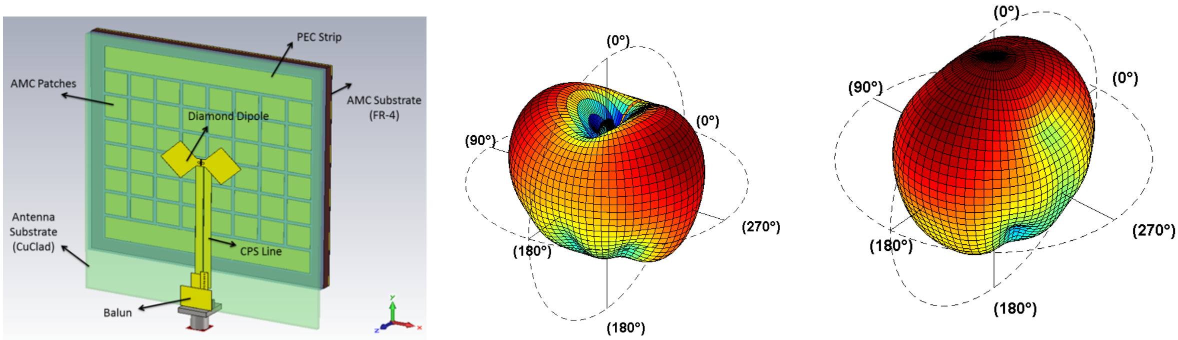
Figure 2.3: Low profile antennas using HIS as Artificial Magnetic Conductor (AMC).

Achievements:

Several contributions have been proposed during my post-doc at Telecom Paristech (2011-2012) [11, 12, 13, 14, 15, 16, 17].

The radiating element and the AMC are usually designed separately before their integration (see figure 2.4a). The effect of their coupling is therefore compensated by numerical optimizations based on the antenna's matching bandwidth. However, splitting effect on the radiation pattern can be observed in some configurations, especially with large AMC reflectors (see figure 2.4b at 0°). In this context, we proposed a method to identify the current on the AMC responsible of this splitting, in order to help optimizing the design to cancel these currents and recover a main beam in the broadside direction (see figure 2.4c at 0°).

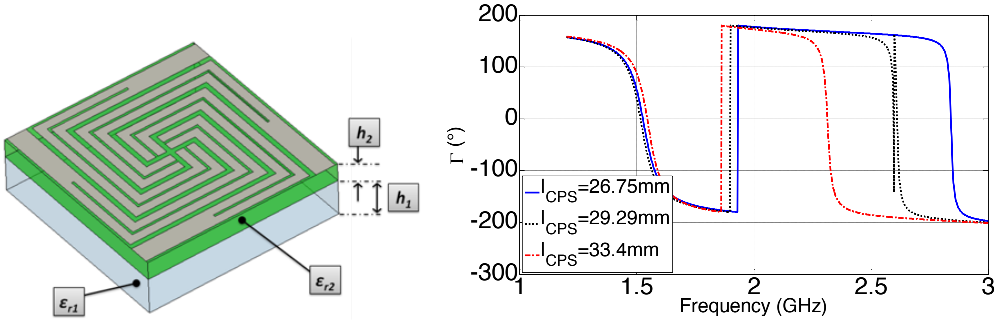
HIS exhibit AMC behavior over a limited frequency range since this property is based on the resonance of the surface. For dual-band applications, such as with GPS for instance, dual-band antennas can be designed but HIS would also need to be dual-band. To that aim, we proposed a dual-band periodic spiral pattern (see figure 2.5a) for which each frequency band can be adjusted independently from each other as shown in figure 2.5b. An analytical model



(a) Diamond dipole over a HIS (b) Radiation pattern of the initial structure (c) Radiation pattern of the "corrected" design

Figure 2.4: Example of the result of the proposed current analysis method [15, 17].

has been also proposed which defines a relationship between the dimensions of the design to the operation frequencies. Furthermore, ratio as low as 1.2 have been achieved between the lower and upper frequencies. Another approach to overcome the HIS limited bandwidth is to design surfaces with multiple spatial periods. To do so, we investigated circular lattices that are well suited to achieve multiple spatial periods for spiral antennas.



(a) HIS periodic pattern to achieve dual-band operation. (b) Reflected phase diagram where the upper band can be independently ajusted

Figure 2.5: Dual-band operation High Impedance Surface [11].

HIS being resonating surfaces, if losses are introduced onto the HIS periodic patterns, it can act as an absorbers. We used this property in order to develop low profile and light absorbers for space applications (the goal was to cancel the reflection of the waves transmitted by a radar on the satellite structure since these multiple reflections were decreasing the accuracy of the radar [13, 14, 16]).

2.1.3 Body Area Networks

Body Area Networks (BANs) are sensor networks that are embedded on the human body and provide useful healthcare monitoring such as EEG, ECG, blood pressure... The use of wireless technology to interconnect sensors enables practical and seamless means to monitor patients.

As sensors get more and more miniaturized for the patient comfort, the autonomy of such technology becomes an issue since the room for the battery becomes limited. In this context, we investigated wireless communications in BAN, which is a critical aspect regarding power consumption, with a particular focus on the understanding of the complex propagation phenomena that take place in the human body vicinity. To this aim, we performed, along with our colleagues from ULB in Brussels, extensive channel modeling with two different approaches. A deterministic electromagnetics approach allows understanding the physics of the propagation mechanisms [18, 19, 20, 21, 22, 23]. A statistical approach provides channel models required to assess communication performance [24, 25, 26]. In doing so, dedicated antennas have been designed to measure the channel, particularly in the 60 GHz band. The complex problem of how to characterize the performance of the antenna once on the human body has been also tackled [27]. In addition, On-Off-Keying (OOK) modulations that are promising for low energy consumption and considered in the 802.15.6 standard have also been assessed and its potential highlighted [28]. Applications related to e-health have been investigated in collaboration with colleagues from UTC in Compiègne [29].

Whether based on a deterministic or statistical approaches (see respectively figure 2.6 top and bottom right), the channel modelling we have conducted intends to determine the attenuation/transfer function of the signal transmitted between a node that is embedded on the human body and a node that could be remote (off-body communications) or also embedded on the human body (on-body). In off-body communications, the human body induces a shadowing that is severe, especially at millimetre-wave frequency such as 60 GHz. To investigate this shadowing, we assumed the human body geometry as a dielectric cylinder whose complex permittivity is similar to the human skin in order to be able to determine analytically the field reflected and diffracted by such an object, as previously done by ESYCOM in Marne-La-Vallée for lower frequency in [30]. This approach led to a simple expression to quantify the shadowing effect on the signal attenuation, which we experimentally showed was accurate enough to describe the attenuation on a real human body [18, 19], and yet compatible with stochastic-based ray tracing channel model such as the IEEE 802.11.ad [25]. The diffraction around the human body, analytically described by creeping waves for curved surfaces or Norton theory for flat surfaces [22], can ensure the communication to some extent even in Non-Line-Of-Sight (NLOS) situations. While we observed the same phenomena for on-body communications [20, 21], we found that such deterministic models appear less relevant in this case due to the large variability of body movements (e.g., breathing, etc.). To that aim, measurements at 60 GHz have been conducted and channel models have been derived based on certain statistics. For instance, we observed a strong fading effect due to the breathing (especially for nodes near the chest area) and we therefore characterize the breathing Doppler power spectral density. We derived path losses for horizontal and vertical links on the body but large deviations have been observed on the developed model, regardless the considered field polarization with respect to the human body surface [24]. We consequently focused our research on scenario-based models rather than models where the distance between nodes is a parameter. In this context, characteristics such path loss [31], or even Bit Error Rate [28], were simply dependent on which limb the node was worn and on which activity the person was doing (e.g., sitting, running, etc.). Furthermore, the license-free band at 60 GHz being very large (from 5 GHz up to 9 GHz depending on the considered country), we also investigated the behavior of wideband channels in off-body scenarios [26]. We show how the location of the on-body antennas influences the power delay profile of the first path and multipath clusters in line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios, independently of the node.

While performing channel modelling and assessment, we had to develop our own dedicated

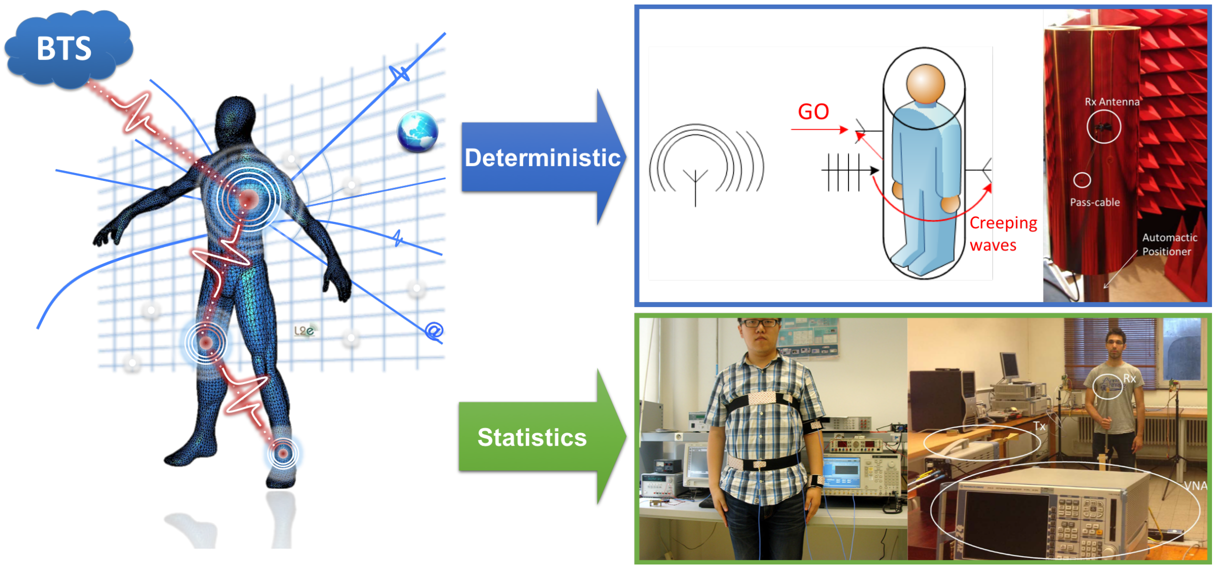


Figure 2.6: Investigation on wireless communications in Body Area Networks.

antennas to meet the requirements of our measurements (see figure 2.7). In this context, we designed and fabricated a low profile planar horn antenna in Substrate Integrated Waveguide (SIW) technology able to cover the whole 7 GHz bandwidth at 60 GHz while exhibiting a polarization orthogonal to the human skin [32] (such a polarization has been found more suitable to establish on-body links). While characterizing this antenna, we show that for on-body configurations, the classically-defined far-field antenna gain depends on the observation distance. Therefore, we proposed to assess the performance in terms of radiation efficiency and link budget [27].

A thorough analysis on the coupling between on-body antennas and the human body led us to conduct a dispersive analysis of the multilayer structure exhibited by the human body (skin/fat/muscle) in order to assess the possibility to use guided wave within the human skin [23]. We showed that this type of propagation could be possible and could allow secure communications between sensors on the human body up to few tens of centimeters in the 3-10 GHz band. However, although a suitable propagation mode exists, it appeared quite challenging to efficiently excite it from the top of the human skin.

2.1.4 Localization

In telecommunications, the knowledge of user's location is important for a number of applications or for optimizing the management of a given network (e.g., smart routing) and hence to decrease the overall power consumption. However, it still remains challenging to accurately and efficiently estimate locations in many situations. In this context, we proposed, along with our colleagues from ULB, an interferometry-based approach to estimate Time Difference Of Arrival (TDOA) in wideband signals with low added complexity thanks to the use of knowledge that is already available in today's communications such as channel estimation in OFDM schemes for instance. This scheme has been investigated in the sub-6 GHz range and in the 60 GHz frequency band [33, 34].

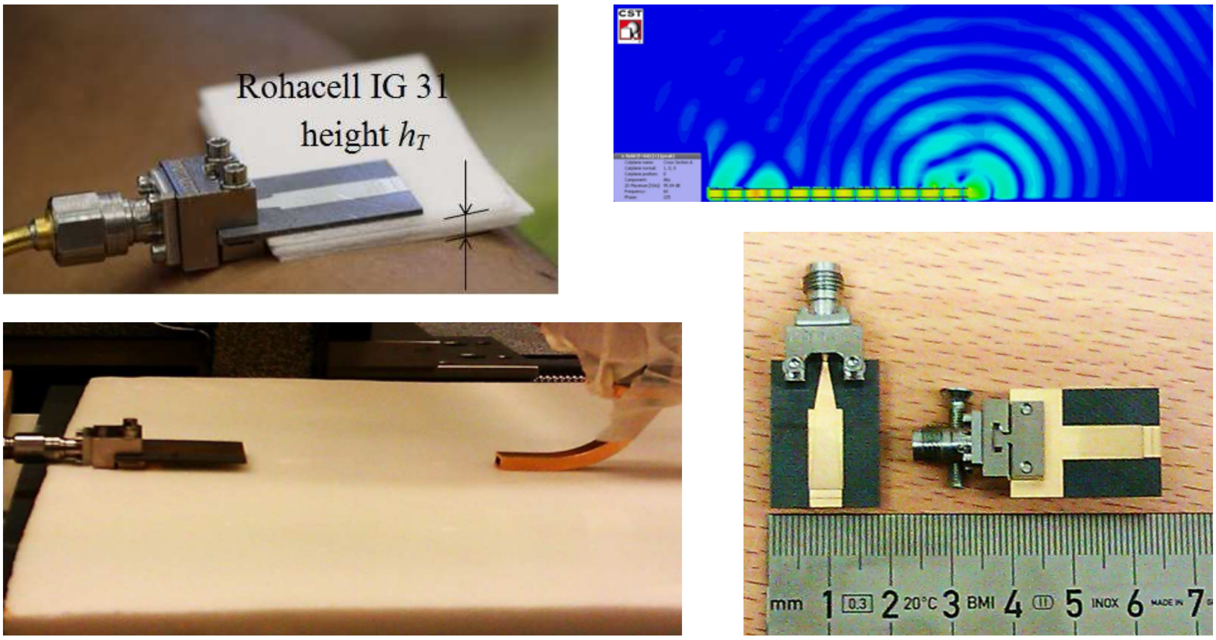


Figure 2.7: SIW horn antenna (bottom right) and its characterization on a fantom in simulation (top right), in measurement (bottom left), and on a person (top left) [32].

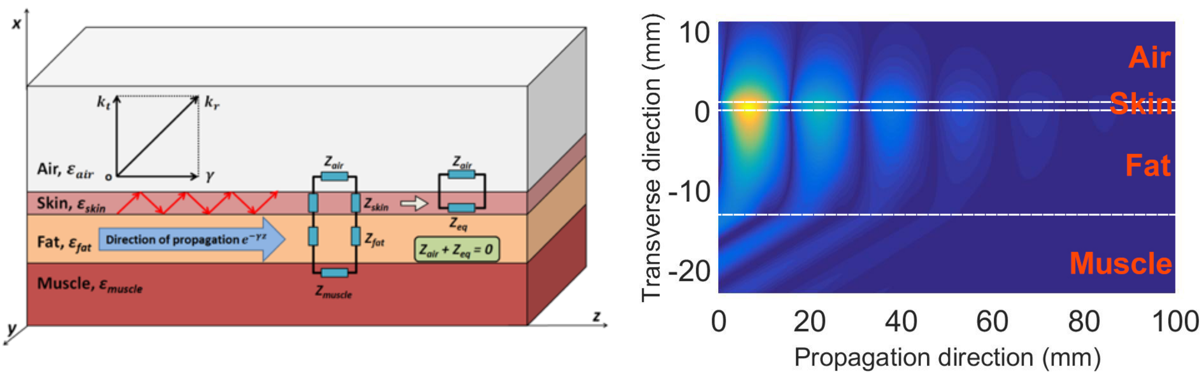


Figure 2.8: Assessment of on-body skin-confined propagation: Dispersive analysis (left) and Field visualization of the determined suitable mode (right).

TDOA concept:

Let us consider a mobile user (MU) that receives two signals transmitted by two different base stations (BTS) such as in figure 2.9. If the MU knows the BTS locations and is able to determine the Time Difference of Arrival (TDOA) between those two signals, the MU can therefore position himself on an hyperboloid. Estimating accurately this TDOA is a challenging task because of the synchronization required between base stations.

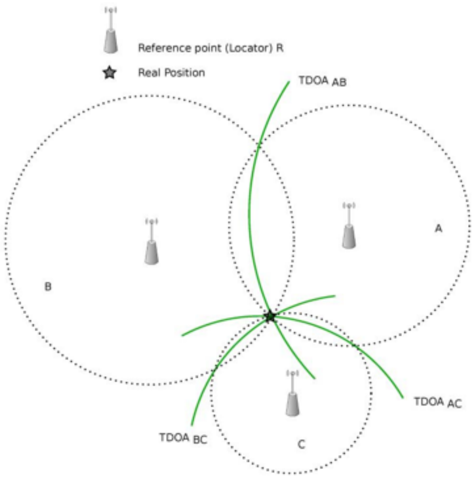


Figure 2.9: Positionning using Time Difference Of Arrival (TDOA) estimation.

Achievements:

To suppress the synchronization constraint, we proposed an interferometry-based method where a single base station transmit the same signal with two different antennas (MISO configuration, see figure 2.10). This induces some deterministic fading in the spectrum at the receiver from which it is possible to estimate the TDOA (see figure 2.10b). In this way, there is no need of synchronization between BTS since it is a single transmitter that feeds two different antennas. However, the distance between those antennas, i.e., the baseline, being smaller than the common distance between two distant BTS, it becomes difficult to retrieve accurately the TDOA, especially of small values. We compensate this effect by taking advantage of the wide-band available at 60 GHz and by developing suitable estimation methods based on minimizing the error between the estimated channel and a direct model. The fading introduced by this interferometric method does deteriorate the signal received by the MU (see the spectrum in figure 2.10b). However, considering OFDM communications, only a limited number of subcarriers are actually impacted by these effects, and the overall EVM or BER remains acceptable. One should emphasise that the fading is readily available in modern communications thanks to the channel estimation. So the added complexity remains limited as we take benefit of a knowledge that is already available in the communication process.

2.2 Ressources: people, funding, and equipment

2.2.1 People

Since I joined Sorbonne (formerly UPMC) in September 2012, I have been involved in the co-supervizion of PhD students, Post-docs, and master students. The figure 2.11 summarizes the

Chapter 4

The research project: Mastering spatial resources

Since my master internship in 2005, I have acquired different research-oriented skills thanks to the different people I have met during my career. My research project for the coming years described in this chapter, intends to take benefit of these different skills (i.e., antennas, propagation channel, and more lately in wireless communication systems) in order to propose an original approach for current challenges in electrical engineering.

4.1 The project topic

Wireless transmissions inherently exhibit a low efficiency due to the unbounded nature of the guiding medium, i.e., the air, and therefore require a high degree of optimization in order to ensure a desired functionality in the context of spectrum congestion due to a constantly increasing number of connected devices. Consequently, these last decades have witnessed intensive research to determine the best way to exploit time and frequency resources (e.g., MIMO communications and radar, beamforming and diversity...). However, spatial resources are yet underexploited and this aspect has now become critical for the deployment of future technologies such as IoT for instance. In this context, the research project I propose encompasses different complementary approaches in order to efficiently exploit spatial resources. Whether to offer new capabilities to systems or to find a way to achieve sustainable high density communication networks, the proposed project addresses scientific fields ranging from electromagnetics to signal and digital communications in order to achieve new solutions. Efficient exploitation of wireless spatial resources are mainly based on the capability for a system to know the location of the device with whom he wishes to communicate, and on the ability to transmit a signal in a particular region in the 2D or 3D physical space. The first ability is known as localization and the second one as focusing. This project proposes to tackle issues encountered in both of them, in the fields of communication and detection.

In this context, among the activities I have been working on since my position at Sorbonne University in 2012, some will stop (Body Area Networks), some will continue (antenna design and localization), and some will start (Spatial Data Focusing). However, my main research contributions still lie in the field of antennas and propagation. While spanning all the aspects of the research project, this chapter emphasizes more the research tasks that are completely new.

4.2 Mastering spatial resources: Focusing

The first approach proposed in this project is to investigate a solution that enables focusing the transmitted data rather than focusing the transmitted power as classically done with antenna arrays (e.g., beamforming). The idea is to process the data in order to be decodable only at a predetermined spatial location. This scheme can overcome the classical limitations of beamforming techniques where the antenna arrays have to be large in order to focus the radiated power within a limited-size area. The proposed technique, i.e., focusing only the data, is spatially more selective than focusing power and is therefore well-suited in the context of sub-6 GHz wireless communications. When operating at higher frequency ranges, focusing the power is a viable option as radiating devices of reasonable size can achieve narrow beamwidths and therefore, achieve high spatial selectivity. In this context, the second proposed approach investigates the design of radiating structures dedicated to specific detection applications in the 60 GHz and THz ranges. The idea is to manipulate radiated waves in order to efficiently create narrow beams that exhibit certain properties such as frequency scanning for remote human's vital sign detection at 60 GHz or beam splitter for multipixels THz space observation.

4.2.1 Spatial Data Focusing: GEOHYPE

This part of the project, i.e., Spatial Data Focusing (SDF), is probably the most innovative aspect of this chapter and will be consequently emphasized and explained in more details. It has received a research grant from the French National Research Agency (ANR) under the young research program (ANR JCJC). The ANR project title is GEOHYPE, standing for *GEOcasting for HYPEr resolution spatial data focusing.*

Objectives

Associating wireless information to certain physical locations is an interesting feature that many applications can benefit from. This capability is known as geocasting. Just like pictures can be tagged with the location where they have been clicked, geocasting enables to tag a real physical location by wirelessly transmitting data that are only decodable within desired delimited areas. Thus, users can receive information related to the place where they are. This is what is achieved to some extent by applications like Google map where metadata related to user's location are sent. To do so, GPS coordinates of users are required. These systems are limited in terms of spatial resolution, especially in indoor environments, and necessitate some time to calculate user's locations, thereby introducing a delay, which can be a limitation in terms of applications. Furthermore, as a general matter, all systems that are based upon user's locations lead to privacy issues. The geocasting scheme proposed in GEOHYPE is fundamentally different. The idea is to transmit data related to locations whether a user is present or not. So instead of considering a user who locates himself with respect to a global reference system and then correlate his position to some databases to discover surrounding locations of interest, the user is able to read the data only when he is located at the right spot. In that case, it is really the location that is tagged, and not the person. This approach therefore respects users' privacy and does not introduce any delay as the data is always sent to the desired location (it is up to the user to decide whether or not he wants to listen). Furthermore, since GEOHYPE does not require positioning capability, all the classical positioning system infrastructure (satellites, multiple synchronized base stations. . .) is not required anymore. The only added infrastructure will be the capability for base stations to focus data to specific spots. For this scheme to be attractive enough, this feature has to be performed with minimum complexity, low cost, and compact size. To date, no existing techniques are capable of realizing the geocasting scheme without hardware that is too complex, too expensive, too bulky, and too demanding in terms of energy.

Consequently, GEOHYPE's focus is to investigate physical solutions that enable the broadcasting of information to specific spatial locations, using limited infrastructures. From a scientific point of view, the problem is to find a way for a base station to wirelessly transmit data that are decodable only within desired areas.

State of the art

Geocasting is classically defined in wireless networks as the capability to send packets to nodes within a certain geographic area [43]. Optimal geographic routing algorithms are investigated to avoid global flooding in networks in order to decrease consumption in terms of bandwidth and power [44, 45]. However, geographic routing-based techniques exhibit a limited spatial resolution, which is strictly related to the base station coverage. To overcome this limit, GEOHYPE investigates a physical solution to spatially confine information in 2D areas with simple and limited infrastructure.

To achieve spatial data focusing (SDF), a first approach is to consider the base station that transmits a signal able to focus its radiated power to a certain location. In that way, the received signal strength is sufficiently large only at this location and therefore, the signal can be decoded only within the desired area. This is classically achieved by beamforming techniques. The transmitter uses an antenna array, where constructive interference occurs between electromagnetic waves radiated by each array element toward a desired direction. An array arranged along a 1D lattice exhibits 1D-focusing capabilities whereas a 2D lattice enables 2D focusing, which is often sufficient for most applications. So in a geocasting scheme, if beamforming is to be used, tagging locations by transmitting relevant data will be equivalent to create beams toward these locations. The data-focusing feature is provided by a radiated power focusing capability. Although this option appears feasible, beamforming suffers from a number of drawbacks that often prevent its practical implementation. The first drawback is related to technological aspects. Antenna arrays usually need a complex control (magnitude and phase) over input signals feeding each antenna array element. This usually leads to high-power consumption, large system size, and high complexity in the design. This type of technology is therefore mainly encountered in military radar systems and spatial applications [46]. Switched-beam arrays address this issue by using passive beamformer networks combined with switches [47] or discrete-step phase shifters [48], which enable the array to switch between a predetermined number of beams. Although this approach simplifies the structure, the number of beams is usually limited and 2D scanning is rather challenging to achieve. But more importantly, **beamforming and switch-beam arrays suffer both from the same fundamental physical limitation. The beamwidth, hence the size of the illuminated area, is strictly related to the electrical size of the array.** Considering that some indoor applications may require geotagged areas as small as tens of centimeters, the size of the required array would be too large, especially if classical GSM frequency bands below 6 GHz are used. In 5G, millimeter-wave frequency bands are investigated and could enable the use of reasonable size antenna arrays, at the expense of complexity. However, at these frequencies, electromagnetic waves do not travel through human body or walls. So these bands are too strongly environment-dependent to achieve a robust geocasting scheme, especially because of shadowing effects.

Two approaches are available in the literature to reduce the number of antennas required to exhibit enhanced power focusing. The first one is based on time-reversal [49]. This technique uses the rich multipath nature of some environments to provide spatial focusing capabilities. However, this requires channel knowledge at the transmitter and the focusing performance depends on the channel properties. High spatial resolution is obtained in highly scattering environments only. Furthermore, the necessity to sample the channel impulse response can make this technique costly in terms of practical implementation [50].

The second approach uses Ultra Wide-Band (UWB) technology. UWB arrays exhibit enhanced angular resolution with respect to narrow-band systems for a given number of antenna elements [51]. UWB arrays naturally take advantage of the fact that the spatial interference of the waves transmitted by each element of the array depends on the frequency. The only direction along which the transmitted waves are in phase over the whole operating frequency range is the broadside axis (assuming that antenna elements are fed in phase). The radiation pattern of a UWB array being defined as the total radiated (or received) energy over the bandwidth with respect to the angular direction [52], grating lobe effects are therefore mitigated. Indeed, side lobe nulls and maxima do not occur at the same angular direction for different frequencies over the operating bandwidth and are therefore mitigated when integrated with respect to the frequency. Consequently, sparse arrays can be achieved in UWB, which enables maintaining focusing capabilities while decreasing the number of required elements [53]. However, two limitations still remain. The first one is that the peak side lobe level still depends on the number of elements. For instance, if a two-antenna UWB array is used, the ratio between the main lobe and side lobes is limited to 3 dB only. So **UWB arrays still need a certain number of antennas** to exhibit expected performance and the **complexity of the whole system** hardware **remains high** because of large bandwidths involved. The second limitation, like with narrow-band arrays, is related to the physical relationship between the overall array aperture and radiated beamwidth. Although with UWB, fewer antennas may be required, the overall size of the array (taken as the distance between antennas located on the array edges) is still large.

GEOHYPE approach is radically different. We propose to change paradigm in order to overcome the physical limitation of power spatial focusing. The idea is **not to try focusing the power to a specific area but only the data**. In other words, the transmitted data are present everywhere but decodable only at the desired location(s). The concept is illustrated in figure 4.1 where **many antennas are required** in order to generate three radiated beams toward three different locations through beamforming (on the left), and where **only a limited number of antennas is used to focus** three different data towards three different locations (on the right). The drawback with this approach is that there is no power focusing with the proposed approach. The signals transmitted by the antennas are not correlated, as it will be seen in the next sections, and therefore no array factor is achieved. The radiation pattern of the dual-antenna array is similar to the pattern of the single element, being directive or not, depending on its topology and size.

So compare with beamforming, SDF exhibits a loss of efficiency at first sight. However, beamforming networks are complex structures that usually consume quite a lot of power (multiple amplifiers or ADCs. . .). Here, the system is much simpler (less antennas) and thereby does not introduce this extra power consumption. Also, one can argue that, in existing GSM networks and classic telecommunications schemes, there is no power focusing either. The signal is transmitted from the base station into the whole cell to illuminate all users within the cell. The approach here is pretty similar as a base station is supposed to radiate within a whole cell in order to illuminate all targeted locations.

Figure 4.1: Example of geocasting with Beamforming (on the left) and with Spatial Data Focusing (on the right).

The concept

The principle of SDF is illustrated in figure 4.2, using a MISO architecture. The multiple antenna system is located at the base station (BTS) while the mobile user (MU) is equipped with a single antenna. $s[n]$ is the symbol stream to be transmitted by the BTS. The symbols are firstly mapped onto an orthogonal space of N dimensions where $s_i[n]$ represents the projection of the n^{th} symbol onto the i^{th} dimension, where $1 \leqslant i \leqslant N$. The dimensions are represented by a set of N orthogonal functions $\Phi = \Phi_1, ..., \Phi_i, ..., \Phi_N$. The choice of this set Φ is an important criteria as it influences the performance of the SDF scheme as well as the management of time and frequency resources. This set Φ is later discussed through specific examples. After filtering, N baseband signals are obtained: $x_1(t), ..., x_i(t), ..., x_N(t)$. Each signal is then converted into the analog domain and up-converted to the carrier frequency before being transmitted by an individual antenna.

The MU consequently receives the sum of the N transmitted signals. Depending on his position with respect to the base station, i.e., depending on θ, the N signals are received at the MU with different delays and phases that correspond to the different distances over which the signals propagate between the N BTS antennas and the MU location.

Since the N transmitted signals are not correlated[1], no interference pattern, i.e., no array factor, is observed. However, the N transmitted signals reaching the receiver with different delays, the orthogonality of the N-dimension space will not be conserved after demodulation at the receiver, except when the MU is in the broadside direction with respect to the BTS antenna array (or any predetermined direction if a phase distribution is used to feed the antennas at the BTS). This will introduce errors in the estimation of the received symbols. In classical beamforming, the received symbol estimation starts to fail when the MU moves away from the main beam because the received Signal-to-Noise Ratio decreases. We show after that acting on the orthogonality of the constellation as we do in SDF is much more effective than beamforming

[1]The projections $s_i[n]$ of the symbols $s[n]$ are not correlated between each other assuming the symbol stream is a random process.

in terms of angular selectivity, i.e., the angular range within which the BER is below a reasonable threshold is much smaller with SDF than with beamforming.

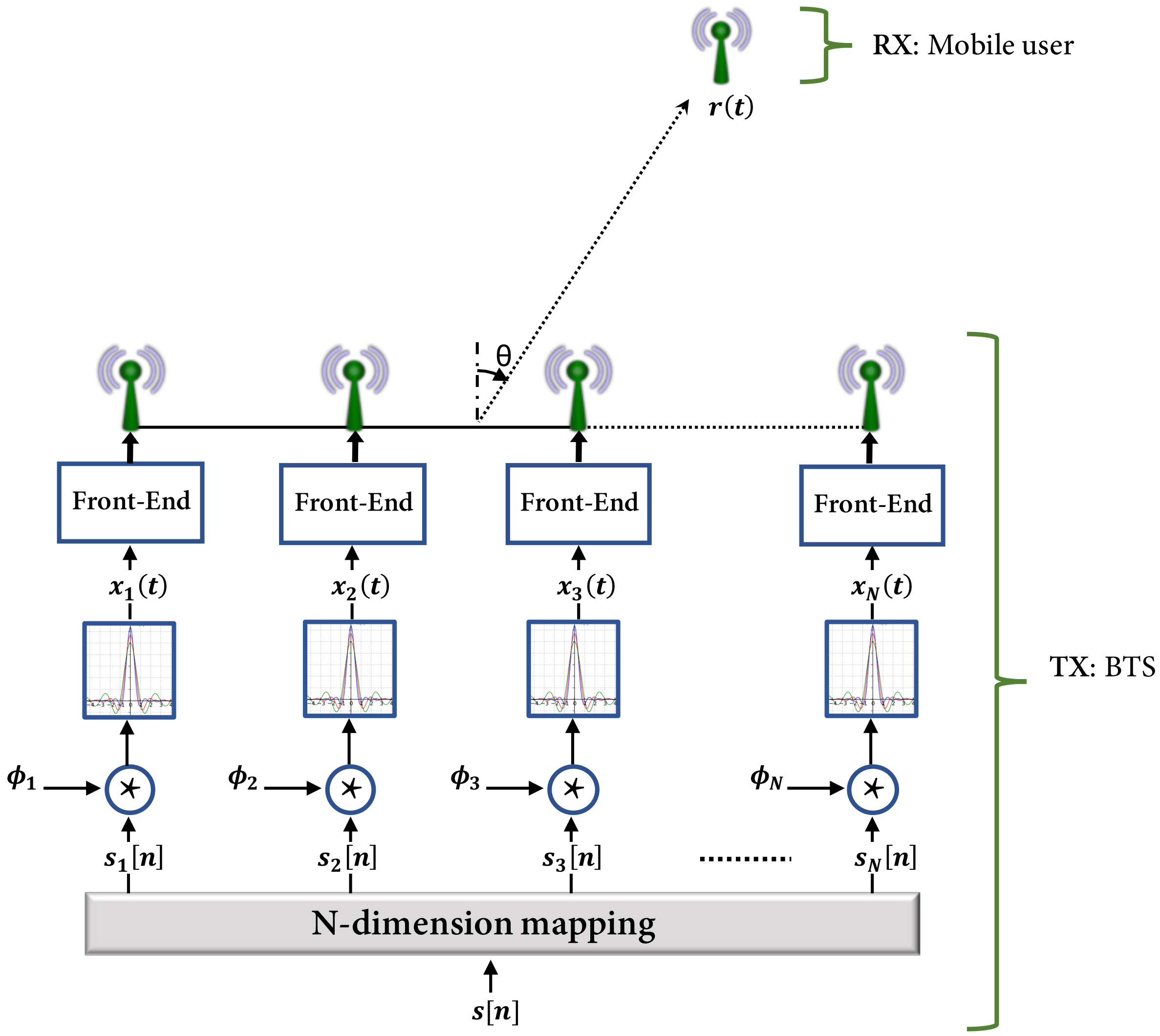


Figure 4.2: Architecture for Spatial Data Focusing.

Position of the project

By focusing the data instead of the power, SDF can overcome beamwidth limitations of classical antenna arrays in wireless geocasting scenarios. When the user is not located within a predetermined beam with respect to the multiple-antenna base station, the received signal is deteriorated as the orthogonality of the constellation is not preserved. This is somehow similar to Directional Modulation (DM) techniques, where constellations are disturbed out of the main beam of an antenna array, in order to avoid an eavesdropper retrieving the transmitted data by receiving the signal from a side lobe directions of the antenna array. Therefore, degrading the transmitted symbols in the side lobe directions is done for a security purpose. However, DM's aim being different, the developed techniques are also different from the ones presented here. In DM techniques such as in [54], the goal is to maintain the antenna array radiation unchanged while deteriorating the constellation outside the main lobe direction, thereby achieving both power and data focusing. In doing so, the beamwidth within which the received BER is low, is about the same size than the halfpower beamwidth of the array factor. By releasing the power focusing constraint, SDF achieves much narrower beams, at the expense of a smaller power efficiency.

Preliminary results: example of a 2-D SDF scheme using IQ resources

To illustrate the SDF concept, we succinctly present here an example using two dimensions, hence two antennas, as shown in figure 4.3. The transmitter uses Quadrature Amplitude Modulation (QAM) and instead of combining the In-phase (I) and Quadrature (Q) signals, I and Q are separately transmitted over two different antennas. This architecture is equivalent to the one in figure 4.2 where $N = 2$ and $\Phi_1 = 1$ and $\Phi_2 = j$. The MU receives a combination of these two uncorrelated signals affected by a different phase and delay, depending on its position. So when θ changes, the received I and Q signals will be more or less orthogonal and the constellation will be disturbed accordingly (as illustrated in figure 4.3), which may or may not enable the receiver to retrieve the data. It is to be noted that this scenario has been also considered in DM techniques in [55], although not deeply investigated.

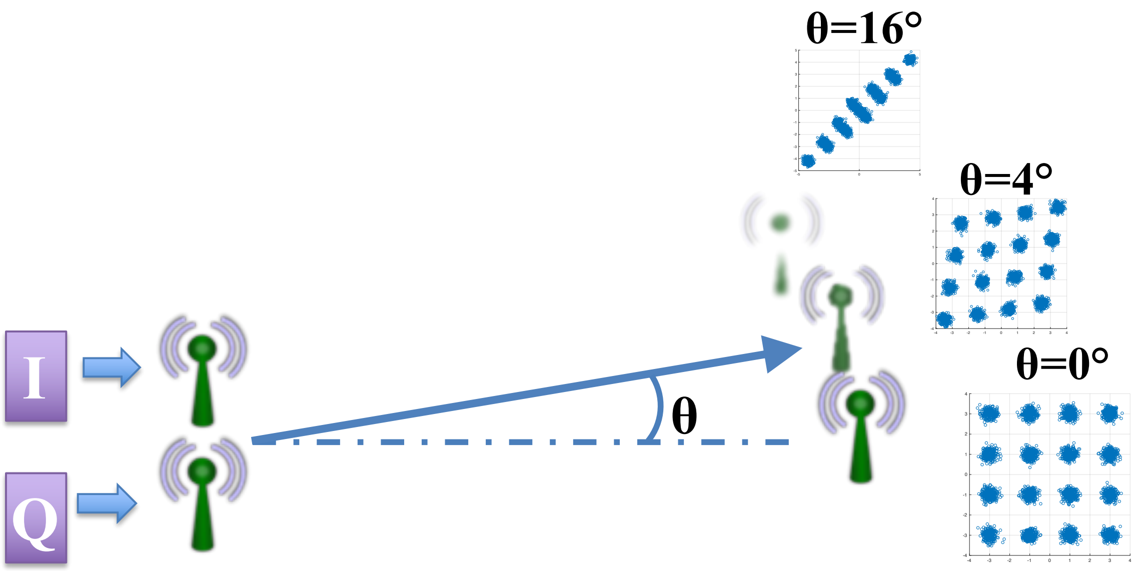


Figure 4.3: 2-dimension Spatial Data Focusing scenario.

Some simulations have been performed in Matlab with ideal isotropic antennas and results are shown in figure 4.4 by considering a 16-QAM modulation, a received Signal-to-Noise-Ratio SNR = 20 dB, a distance between transmitting antennas $b = 0.75\lambda$ (where λ it the wavelength at the carrier frequency), a carrier frequency $f_c = 2.1$ GHz, and a bandwidth $\Delta_f = 20$ MHz. The blue curve is the BER obtained with the data focusing approach while the orange curve is the BER obtained with classical beamforming, i.e., I and Q signals are added together and then sent to both the antennas. It can be observed that the angular range over which the BER is below a certain threshold, e.g., 10^{-3}, is much narrower with SDF ($\theta_{BER=10^{-3}} = 6.4°$) than with beamforming ($\theta_{BER=10^{-3}} = 39°$). Furthermore, in this particular example, other angular directions exhibit BER less than 10^{-3} in beamforming (at $\theta \pm 90°$). Indeed, if side lobes exist in the array factor, it can also introduce side lobes in the BER, depending on the SNR. We now define the beamwidth as the angular range over which the BER is below 10^{-3} instead of the half-power beamwidth as classical used in antenna theory.

It is to be noted that for comparison purpose, the BER at $\theta = 0°$ is identical for both SDF and beamforming scheme. This means that less power has been used for the simulation with the beamforming (-3 dB), since only this last scheme benefits from the 3-dB array factor. Also, in the presented scenario, where no phase shift is introduced between the two TX antennas, the geotagged area is located in the broadside direction (i.e., $\theta = 0°$), but a phase distrbution introduced in the feeding (like in classical beam steering scenario), can shift this direction to any angular region.

The beamwidth variation with respect to the distance b between the TX antennas is shown in figure 4.5. It can be observed that like in classical beamforming, the greater the distance b, the narrower the beamwidth. However, SDF schemes have additional degrees of freedom to adjust the beamwidth over which the BER is low, such as the mapping. For instance, a 64-QAM exhibits narrower beamwidth than 16-QAM. Though the constellation size may not be a practical degree of freedom, we aim at showing that more degrees of freedom exist, especially if more than 2 dimensions are used, as mentioned in the perspectives of this project

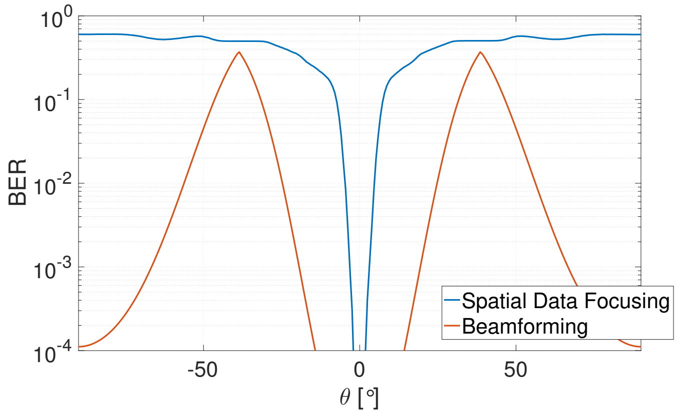


Figure 4.4: BER results for 2D-IQ-SDF scheme for a 16-QAM with SNR = 20 dB ($E_b N_0$ = 14 dB), $b = 0.75\lambda$, $f_c = 2.1$ GHz, and $\Delta_f = 20$ MHz.

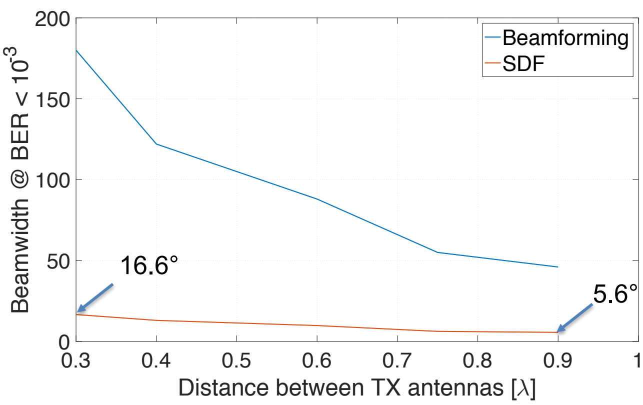


Figure 4.5: Influence of the inter-antenna spacing b on the BER beamwidth for a 16-QAM with SNR = 20 dB ($E_b N_0$ = 14 dB), $b = 0.75\lambda$, $f_c = 2.1$ GHz, and $\Delta_f = 20$ MHz.

In order to gain insights regarding how the constellation is affected by the SDF scheme, we quantify the deterministic perturbation on the symbol estimation at the MU as a function of θ. As shown in figure 4.6, s_k is the transmitted signal in the 2D IQ space and $s_k(\theta)$ is the received symbol in the absence of noise. $s_k(\theta)$ is shifted with respect to s_k by a factor μ_I along the first dimension (I) and by μ_Q along the second dimension (Q), because of the delay in propagation introduced by the SDF scheme. μ_I and μ_Q can be calculated analytically and are given in equations 4.1 and 4.2 respectively.

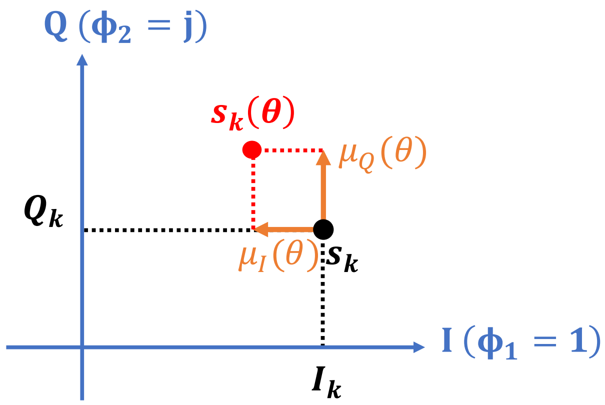


Figure 4.6: Representation of a symbol in the IQ constellation, shifted by SDF effect.

$$
\begin{aligned}
\mu_I[k] =& I_k\left[1 - f(\Delta\tau/2)\cos\pi f_c \Delta\tau\right] \\
&- \cos\pi f_c\Delta\tau \sum_{\substack{n=0 \\ k\neq n}}^{\infty} I_n f\left[(k-n)T - \Delta\tau/2\right] \\
&+ \sin\pi f_c\Delta\tau \left\{ Q_k f(\Delta\tau/2) + \sum_{\substack{n=0 \\ k\neq n}}^{\infty} Q_n f\left[(k-n)T + \Delta\tau/2\right] \right\}
\end{aligned} \tag{4.1}
$$

$$
\begin{aligned}
\mu_Q[k] =& Q_k\left[1 - f(\Delta\tau/2)\cos\pi f_c \Delta\tau\right] \\
&- \cos\pi f_c\Delta\tau \sum_{\substack{n=0 \\ k\neq n}}^{\infty} Q_n f\left[(k-n)T + \Delta\tau/2\right] \\
&+ \sin\pi f_c\Delta\tau \left\{ I_k f(\Delta\tau/2) + \sum_{\substack{n=0 \\ k\neq n}}^{\infty} I_n f\left[(k-n)T - \Delta\tau/2\right] \right\}
\end{aligned} \tag{4.2}
$$

where f_c, is the carrier frequency, $f(t)$, is the pulse shape function (whose spectrum is commonly a raised cosine) used in the modulation, T, is the symbol duration, and $\Delta\tau = \frac{b\sin(\theta)}{c}$, with c, the light velocity. k is the index of the symbol that is currently estimated while n is the index of the other symbols in the symbol stream. I_k (I_n) and Q_k (Q_n) are the projections of the k^{th} (n^{th}) symbol on the two dimensions I and Q (so $s_1 = I_k$ $s_2 = Q_k$ according to figure 4.2).

As θ differs from θ_0 (i.e., broadside if no phase distribution is used in the feeding), $\Delta\tau$ increases. This leads to three different effects that will disturb the correct estimation of the symbol s_k:

1. The correct I_k (or Q_k) amplitude is affected by a factor $-f(\Delta\tau/2)\cos\pi f_c\Delta\tau$

2. Inter Symbol Interferences (ISI) will arise because of the term in the second line in equation 4.1 (or in 4.2)

3. The projection of the symbol on the Q (or I) dimension is not perfect and therefore, part of the energy will be transferred to the I (or Q) dimension (third line in equation in equation 4.1 (or in 4.2)

Observing that the function $f(t)$ decays rapidly away from $t = 0$, one can limit the influence of adjacent symbols to the ones just before (i.e., $k = n + 1$) and just after (i.e., $k = n - 1$) the considered symbol, thereby obtaining:

$$\begin{aligned}\mu_I[k] =& I_k \{1 - f(\Delta\tau/2)\cos\pi f_c\Delta\tau\} + Q_k f(\Delta\tau/2)\sin\pi f_c\Delta\tau \\ &- I_{k-1} f(T - \Delta\tau/2)\cos\pi f_c\Delta\tau - I_{k+1} f(-T - \Delta\tau/2)\cos\pi f_c\Delta\tau \\ &+ Q_{k-1} f(T + \Delta\tau/2)\sin\pi f_c\Delta\tau + Q_{k+1} f(-T + \Delta\tau/2)\sin\pi f_c\Delta\tau\end{aligned} \tag{4.3}$$

$$\begin{aligned}\mu_Q[k] =& Q_k \{1 - f(\Delta\tau/2)\cos\pi f_c\Delta\tau\} + I_k f(\Delta\tau/2)\sin\pi f_c\Delta\tau \\ &- Q_{k-1} f(T + \Delta\tau/2)\cos\pi f_c\Delta\tau - Q_{k+1} f(-T + \Delta\tau/2)\cos\pi f_c\Delta\tau \\ &+ I_{k-1} f(T - \Delta\tau/2)\sin\pi f_c\Delta\tau + I_{k+1} f(-T - \Delta\tau/2)\sin\pi f_c\Delta\tau\end{aligned} \tag{4.4}$$

Furthermore, under narrowband assumptions, $\Delta\tau << T$, so $f(T-\Delta\tau/2) \approx f(-T-\Delta\tau/2) \approx 0$. So equations 4.3 and 4.4 can be reduced to respectively:

$$\mu_I[k] = I_k \{1 - f(\Delta\tau/2)\cos\pi f_c\Delta\tau\} + Q_k f(\Delta\tau/2)\sin\pi f_c\Delta\tau \tag{4.5}$$

$$\mu_Q[k] = Q_k \{1 - f(\Delta\tau/2)\cos\pi f_c\Delta\tau\} + I_k f(\Delta\tau/2)\sin\pi f_c\Delta\tau \tag{4.6}$$

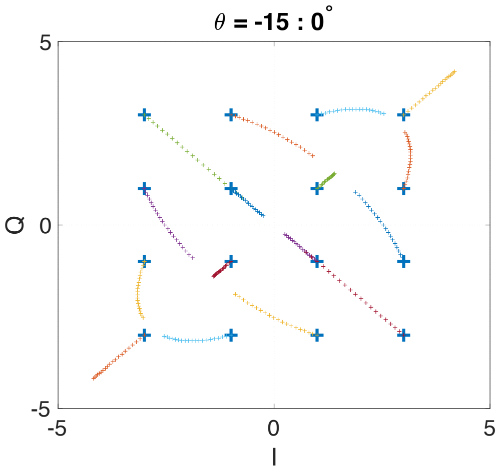
Using equations 4.5 and 4.6, we plot in figure 4.7 the evolution of the constellation over θ on the $[-30° : +30°]$ range. The same simulation parameters than those used in figures 4.4 and 4.5 have been used. The colored dashed lines show the received estimated symbol as θ increases or decreases when no noise is considered. It can be observed that each symbol shifts from its initial location with its own trajectory, each quadrant being symmetric with respect to the origin. Therefore, a simple complex gain estimated at the receiver by measuring the channel will not be sufficient to retrieve the original constellation[2].

The above mentioned SDF example is very simple and yet has the benefit of being compatible with existing IQ transmitter architectures. However, with only two orthogonal signals, and so only two antennas, focusing capabilities are limited to one dimension and in terms of beamwidth narrowness. 2D focusing requires at least three antennas and mapping using more dimensions are consequently required.

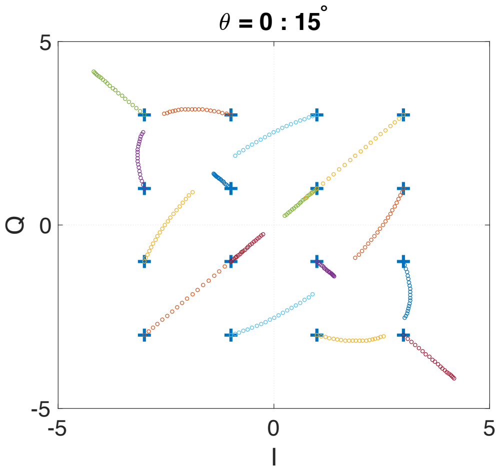
Preliminary results: example of a N-D SDF scheme using time resources

In order to build an N-orthogonal-dimension space, several solutions are possible and we present here preliminary results based only on orthogonal-time pulse, although we have started to work on orthogonal codes and plan to work on orthogonal frequencies as well.

[2]Furthermore, we do consider the receiver cooperative in the SDF scenario and no further processing appart from a classical channel gain estimation for communication purpose is considered.



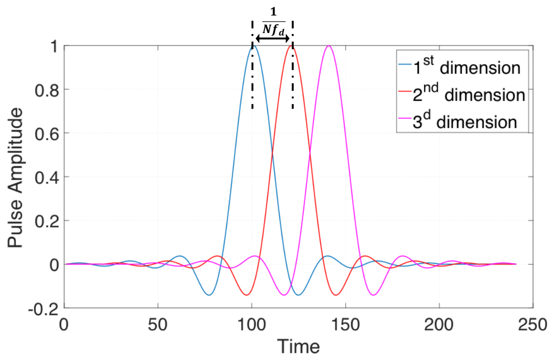
(a)



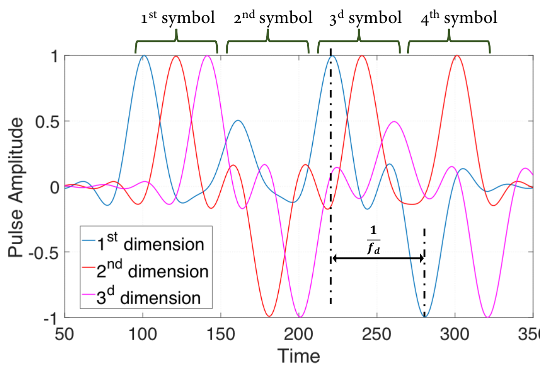
(b)

Figure 4.7: Evolution of the constellation when θ varies from (a) -15° to 0° and from (b) 0° to 15° (SNR = 20 dB, $b = 0.75\lambda$, $f_c = 2.1$ GHz, and $\Delta_f = 20$ MHz).

In the presented example, each of the N dimensions is a pulse (whose frequency spectrum is root raised cosine) that is orthogonal in time domain to the adjacent pulses as shown in figure 4.8a for a 3D example. If f_d is the symbol rate, the time interval between two pulses is $\frac{1}{Nf_d}$. For sake of clarity, only a Pulse Amplitude Modulation is used here. So when mapping a symbol k in this N-dimension orthogonal space, the projections $s_i[k]$ will modulate in amplitude the pulse corresponding to the i^{th} dimension. This architecture is equivalent to the one in figure 4.2 where the functions Φ_i of the set Φ are vectors of length N such as $\Phi_1 = [\,1\,0\,0\cdots0\,]$, $\Phi_2 = [\,0\,1\,0\cdots0\,]$, $\Phi_i = [\;0\cdots1\cdots0\;]$, and $\Phi_N = [\;0\;0\;0\cdots1\;]$. To illustrate the modulation process, figure 4.8b shows the three signals (on per dimension) after modulation and filtering of a 4-symbol stream, that are to be sent by three different antennas. The symbol duration is shown and is equal to $\frac{1}{f_d}$.



(a) 3D space with time-orthogonal pulses



(b) 3 signals of a 4 symbols stream after mapping and filtering. Each signal, i.e., each dimension, is feeding a unique antenna.

Figure 4.8: Example of a 3D time-based Spatial Data Focusing (f_d is the symbol rate).

To illustrate SDF performance based on orthogonal-time-pulse, simulations are performed using Matlab. A stream of 10^5 random bits is generated and symbols of k bits are mapped onto the N-dimension space. BER results are shown in Fig. 4.9 (simulation parameters are given in the caption). When $N = 2$, the beamwidth observed at BER $= 10^{-3}$ is 29.4° when $k = 2$ and 12.8° when $k = 4$, which is similar to the power focusing of a 7-antenna array using 16-QAM. The SDF scheme is therefore interesting since it can achieve the same data focusing performance with a much smaller array. When $N = 7$, SDF achieves a beamwidth of 5° when $k = 7$ and 2.5° when $k = 14$. For a fair comparison, i.e., similar robustness to noise, we compare here $k = 2$ and $k = 4$ in two dimensions to $k = 7$ and $k = 14$ in seven dimensions, respectively. In other words, whatever N, two cases are compared: $k = N$ and $k = 2N$. It is to be noted that when $N = 7$, the symbols contain more bits, so the bit rate is increased. However, to create multiple dimensions, more bandwidth is required. Therefore, as with classical multidimensional modulations, the spectral efficiency remains unchanged when N varies and the overall bandwidth is fixed. Hence SDF may use any number of antennas while keeping constant the bitrate and the robustness to noise.

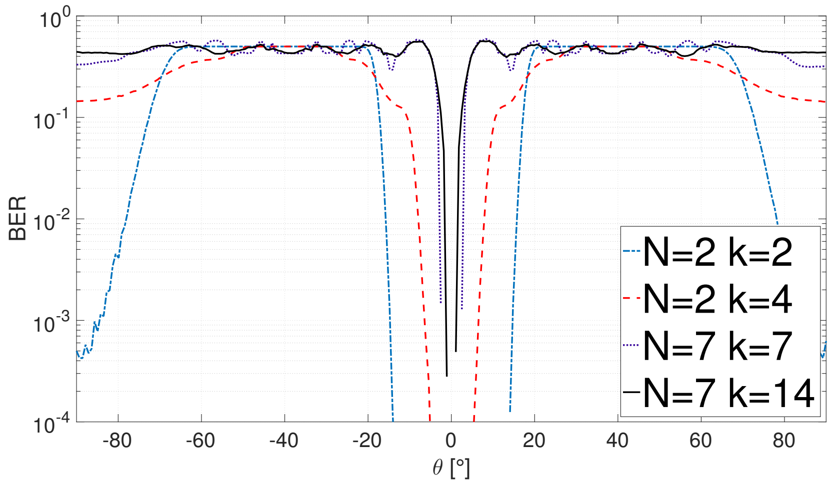


Figure 4.9: BER obtained with a N-antenna array using Spatial Data Focusing scheme. $d = 0.8\lambda$, $f_d = 20$ MHz, roll-off $= 0.75$, SNR $= 20$ dB.

We started studying the effect of the channel estimation on the SDF performance (not presented here) and we have found that depending on how the channel equalization is performed, the BER beamwidth may vary. Consequently, this could be a useful and practical degree of freedom in order to adjust the beamwidth in SDF scenarios.

Workplan

SDF being a new proposed scheme, it is necessary to conduct research in a variety of aspects including mapping and modulation techniques, dedicated filtering, propagation channel influence, channel estimation and equalization, dedicated antenna array design, etc.

So far, working on this project in addition to myself, one can cite Michael Odhiambo (from University of Burgundy) and Sidney Golstein (from ULB). Michael Odhiambo has done his six-month second-year master internship on this project in 2017 and started his PhD on the same topic in October 2017. He is investigating the use of orthogonal codes ($\Phi_{1:N}$, in figure 4.2) to create a multi-dimensional space on which the symbol are mapped before transmission. Similarly to time resources as presented earlier, the use of a code-based SDF scenario enables the use of N antennas and introduces additional degrees of freedom (e.g., code length) to control the performance of the scheme. Sidney Golstein has done his three-month second-year master internship on this project in 2017 and is currently doing his master thesis on the same topic. He has worked on time-based SDF such as presented in the previous sections and has developed a bench using National Instrument USRPs to perform measurements. We are currently asking the EDITE doctoral school of Paris for a grant for Sidney to start a PhD in September 2018 in order to pursue this work by investigating dedicated mappings and channel estimations, carrier recovering techniques, and USRP-based bench development. Another second-year master student, Guylian Molineaux (from ULB), will start his three-month internship in July 2018 on this topic by investigating the channel influence. The idea is to determine the relationship between the channel statistics (Rice factor, MISO channels correlation, etc.) and the performance of the SDF scheme in a real indoor environment.

The ultimate goal is to be able to efficiently achieve SDF with:

- a robust communication within the geocast area
- a sufficient number of degrees of freedom to adjust the size of the geocast areas
- a minimum number of antennas at the base station
- multi-user capabilities
- multi-direction capabilities (i.e., multiple geocast areas, possibly of different sizes)

Once SDF is sufficiently established, the idea is to exchange with different teams, including people working in directional modulations, and to co-organize special sessions. We will also consider designing dedicated antenna arrays to combine power focusing thanks to classical antenna array approach (with fixed beamforming networks) and SDF. This could lead to the design of sparse arrays, for which additional cooperation(s) will be needed.

4.2.2 Power Focusing

At higher frequencies, highly directive structures can be achieved within a reasonable volume, and hence, power focusing appears to be a suitable choice to master spatial resources. Furthermore, power focusing is often necessary to improve link budget or increased sensitivity in detection applications because of the large free space attenuation in millimeter-wave and terahertz (THz) frequencies. For this two different frequency ranges, this research project investigates two different approaches.

THz focusing: reflector and transmit array

In radio-astronomy in the THz frequency range, heterodyne receivers are usually used as they can achieve very high spectral resolution, well suited to observe molecular and atomic transition lines, from which physical and chemical conditions of the interstellar medium can be determined, as well as its kinematics. The observed sky signal is mixed with an artificial monochromatic signal created by a local oscillator (LO). The receivers embedded on satellites are usually limited to the observation of one angular direction, i.e., mono-pixel instruments. Recently, there has been a growing interest among scientists in developing multiple-pixel THz radio-astronomy instruments. To that purpose, arrays of heterodyne receivers are being developed to simultaneously measure spectra at several positions in the sky. This configuration introduces however two major issues. Each pixel includes a mixer and therefore the monochromatic waves produced by the LO needs to be split in order to pump the multiple mixers. Furthermore, building arrays of receivers close to each other imposes additional contraints on the size of each receiver. One bulky component is the lens that is commonly used to focus the received signal from space onto the mixer connected to a single antenna.

In this context, we have proposed and are currently investigating new solutions for these two issues, that are: LO beam splitters and planar transmit array to replace the bulky lens of the receiving antenna. This work is done together with Dr. Massimiliano Casaletti, Associate Professor at L2E, and is a collaboration with Dr. Martina Wiedner from the Observatoire de Paris (LERMA), who designs and builds heterodyne receivers for THz radio-astronomy. Two PhD students have worked on this topic (Fabien Defrance, 2012-2015 [40], and Duccio Delfini, 2015-2018, on-going) and a third one is expected to start in September 2018. The funding comes from the CNES (French Space Agency) and the projects are led by Dr. Martina Wiedner.

We use applied electromagnetics-based techniques to develop designs at THz frequencies, where Geometrical Optics (GO) approximation is usually assumed. Regarding the beam splitter, it is a device that splits an incident beam into multiple beams. The structure may be a lens or a reflector. Although we have investigated both, at THz frequencies, metallic reflectors are very efficient because of their extremely low losses. For beam spitter design, Fourrier gratings are commonly used. It is a periodic lattice that can reflect an incident plane-wave into several beams. While the direction of the beams can be chosen, their shape cannot. Also, the shape of the incident beam is not taken into account and this lead to sub-optimal efficiency. To add more degrees of freedom in the design and to efficiently take into account the oblique incident non-planar wave-front, different optimization methods to design phase-only Diffractive Optical Elements (DOEs) exists in the literature where an Inverse Fourier Transform (IFT) maps the desired radiated field pattern onto the DOE aperture. An iterative process based on alternate projections involving both IFT and FT is then used to converge to an aperture distribution that matches both the desired radiated field pattern and the DOE's physical constraints. In the process, GO approximation is classically assumed at optical frequencies but can lead to non-optimized performance at THz. The beam splitter design procedure we are investigating [41] does not make use of GO approximation but calculates instead the radiated field due to an equivalent magnetic current in the DOE aperture in the optimization process (see figure 4.10).

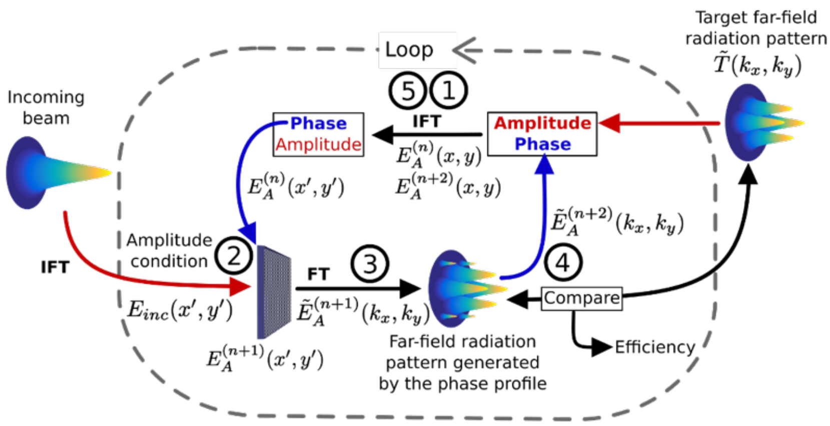
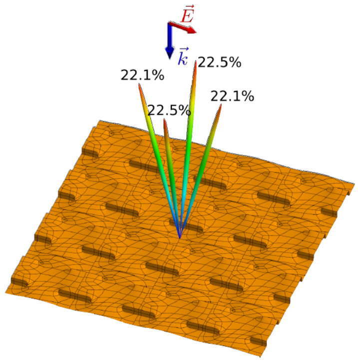
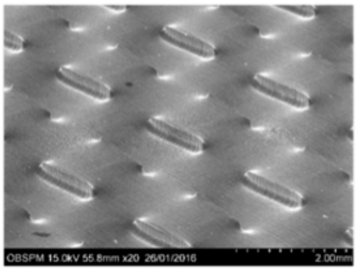


Figure 4.10: Optimization-based beam splitter design procedure [41].

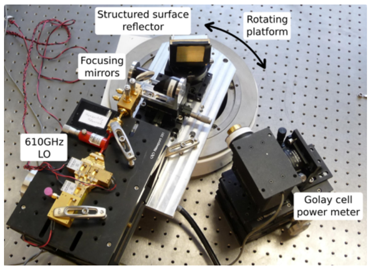
With respect to GO-assumptions-based design procedure, this rigorous approach enables obtaining equal-intensity split beams, required in mutli-pixel instruments (see figure 4.11a). The difference can be explained by the dipolar nature of the reflector's current radiation that is not taken into account in GO, which leads to unbalanced beams under oblique incidence illumination (the intensity of the field radiated by a current element is not isotropic over the beam angles as supposed by GO). A prototype at 610 GHz has been fabricated (see figure 4.11b) and characterized (see figure 4.11c).



(a) Feko simulation of a 4-beams splitting, with field intensity reported.



(b) Photography of the fabricated prototype operating at 610 GHz.



(c) Experimental set-up to measure the radiation efficiency.

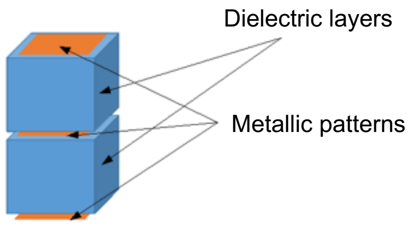
Figure 4.11: Beam splitter [41]

The transmit array we propose in order to replace the bulky lens of the receiving THz antenna, is also based on a structure optimization with respect to technological capabilities. The goal of this planar structure is to confine to a single spot, i.e., the supra-conductor-based THz mixer, the incident plane wave. To do so, we use a periodic structure where each unit-cell must introduce a certain phase shift between the incident plane wave and the transmitted field, while minimizing the reflection of the incident field. Taking into account the fabrication process available by our colleagues at LERMA, we use a triple layer structure as shown in figure 4.12a, where the metallic patterns can be modelled by a surface impedance. The value of the impedances is determined by an optimization using transmission line theory and the metallic patterns are designed to achieve the calculated impedances. Figure 4.12b shows a simulation that illustrates the focusing capability of the transmit array. A prototype has been fabricated for an operation at 600 GHz and is presented in figure 4.12c. The measurement are currently on-going.

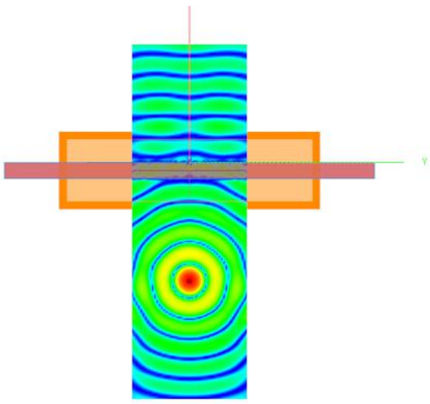
60 GHz focusing: Beam-scanning leaky wave antenna for Doppler Radar

In the context of healthcare, there has been a growing interest these last years to remotely monitor vital signs of human people, such as breathing rate and heartbeat. Indeed, not requiring the person to be monitored to wear sensors, opens new perspectives. Hospitals could benefit from a continuous and seamless monitoring solution that would lead to more comfort for the patient while offering a cost-effective solution since there would be no need to replace the sensors between each patient (non-contact approach). Monitoring respiration and heartbeat rate can also enable detecting emergency situations such as stress or falling asleep for airplane's pilot or bus's driver for instance, or to detect emergency situations among elderly at home.

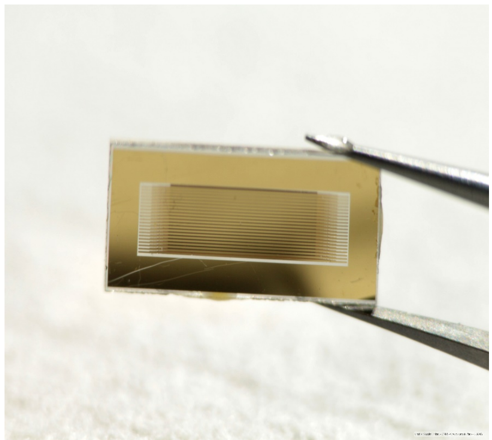
We started to work with my colleague Dr. Guido Valerio (L2E) on the elderly emergency situ-



(a) Schematic of the transmit array



(b) Simulation of the focusing power of the transmit array



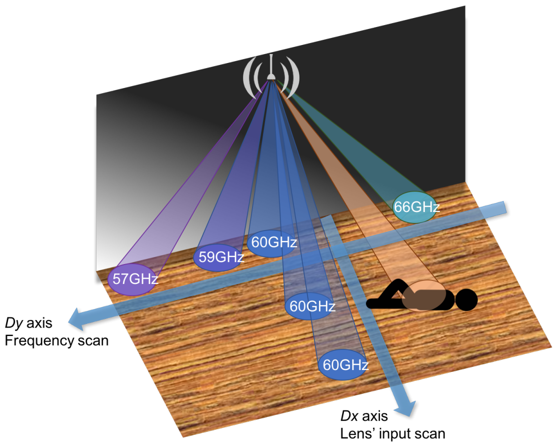
(c) Photgraphy of the fabricated prototype

Figure 4.12: Transmit array.

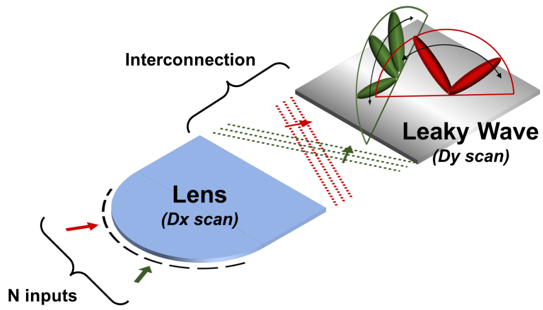
ation detection in a project with Prof. Dan Istrate from UTC, Compiègne. During this project, a one-year post-doc, Dr. Ting Zhang, developed a 60 GHz Doppler radar using laboratory equipment and developed the necessary signal processing that enabled retrieving successfully the breathing rate and heartbeat of a person standing still in front of the radar. In this scenario, we detect the micro-Doppler of the chest movement due to the breathing (few millimeters) and to the heartbeating (about one tenth of millimeter). Thanks to the small wavelength at 60 GHz (5 mm), the Doppler response due to the heartbeat is quite strong.

To pursue this project, we now require the radar to exhibit spatial selectivity in order to remotely monitor a person within a room, who is not necessary standing in front of the radar. In other words, the smart antenna of the radar needs to focus the radiated power within a narrow beam (to achieve angular selectivity) that can be tilted to scan an entire room, such as the scenario presented in figure 4.13a. To do so at 60 GHz, a phased array would be a costly and power-consuming solution. To achieve a lighter solution, we take into account the fact that the radar operation is mono-chromatic. Consequently, we intend to use frequency diversity to achieve a scanning in one-dimension thanks to a leaky-wave antenna. Indeed, the large bandwidth available at 60 GHz can be used for that purpose and we will investigate optimized solutions that enable the scanning of an entire room within the 5 to 9 GHz license-free bandwidth, assuming the radar operation will not be much affected if the frequency used is 57 GHz or 66 GHz (see figure 4.13a). To perform a 2D scanning, we intend to develop a planar lens that will tilt the wave front of a surface wave depending on where the lens is going to be excited (see figure 4.13b). This lens will fed the leaky-wave antenna and therefore offers a scanning in the other dimension (see figure 4.13a)

The challenge here is to design a highly directive antenna based on a highly dispersive planar structure in order to exhibit the largest possible angular scanning range. Indeed, the scanning capabilities of leaky wave antennas are directly related to their dispersion diagrams. When the planar structure on which leaky-wave antennas are based is dispersive, we observe a large angular variation within a limited frequency bandwidth. However in this case, it is often difficult to maintain a well-shaped radiated beam. So we intend to conduct dispersive analysis of complex planar structure, i.e., multi-layer metallic impedance surface, in order to achieve the best possible tradeoff between directive beam and angular scanning range. To do so, we will take benefit of the work conducted by Qiang Zhang (PhD student I am co-supervizing) in dispersive analysis and the skills of my colleague Dr. Guido Valerio (L2E) in periodic structure analysis. Finally, to achieve a full radar demonstrator, we are cooperating with IIT Bombay, India, in the NOVIS60 project, who is going to design a 65-nm Silicon-based front-end for this particular radar (i.e., with frequency agility capabilities).



(a) Indoor beam scanning



(b) 2D beam scanning antenna

Figure 4.13: Beam scanning capability for radar-based indoor vital sign remote monitoring.

4.3 Mastering spatial resources: Localization

While performing localization, regardless the considered positioning technique, the complex phenomena that take place in the propagation channel introduce uncertainties and possibly very large errors in the determined device/user location. The channel is indeed a bottleneck in the localization process. Based on its statistical properties, this project aims to improve positioning technique in adverse environments, with a particular focus on techniques based on Angle-of-Arrival (AoA) detection in 5G's small cells or indoor scenarios. Similarly to focusing aspects, different approaches are considered depending on the considered frequency range, i.e., sub-6 GHz and millimeter waves. Positioning a device in 2D (or even 3D) using AoA requires either multiple base stations (suitable for IoT, i.e., Internet-of-Things, narrowband signals) or additional features such as Time (Difference) Of Arrival for instance (suitable for wideband signals). In the context of multiple base stations using narrow-band signals below 6 GHz, an important issue is the uncertainties introduced by each AoA estimated by each base station. So the project intends to address not only how to efficiently take into account those uncertainties in the positioning process but also how to estimate them based on the channel estimation. With millimeter waves, signals occupy larger bandwidths and therefore more statistical features can be extracted from the channel estimation. Thanks to this additional knowledge, we intend to determine whether the wireless communication is based on a direct Line-Of-Sight (LOS) path or a Non-LOS (NLOS) path. Being able to discriminate both these situations is an important feature to improve positioning accuracy, especially in millimeter-wave bands where shadowing effects are severe.

4.3.1 Localization in the sub-6 GHz band: AoA-based positioning in multiple small-cells environment

For numerous applications of the IoT, localization is an essential element. However, due to technological constraints on these devices, standards methods of positioning, such as Global Navigation Satellite System or Time-of-Arrival methods, are not applicable. Therefore, Angle-of-Arrival (AoA) based localization is considered by using a densely deployed set of anchors, e.g., small cell's base stations, equipped with arrays of antennas able to measure AoA of the signal transmitted by the device to be located. The original method investigated by Thomas Van de Vorst (PhD student from ULB, supervised by Prof. Philippe De Doncker and co-supervised at Sorbonne by Prof. Aziz Benlarbi-Delaï and myself) consists in applying Polynomial Chaos Expansions (PCE) to this problem in order to obtain statistical information on the position estimate of the device [56].

Initially introduced by Norbert Wiener in 1938 with *The Homogeneous Chaos* [57], the theory of Polynomial Chaos Expansions (PCE) is a surrogate modelling technique, through which the response surface of a computational model is approximated using multidimensional polynomials that are orthogonal with respect to the PDF of the input random variables of this model. While PCE are based on standard random variables, e.g., Gaussian or Uniform, to generate the polynomial basis of the expansion, it is possible to use isoprobabilistic transforms in order to apply the theory for any arbitrary random variables. In our case, the computational model is a least squares estimator of the User Equipment (UE) location that takes as inputs the deterministic known positions of the i anchors and the i AoA θ_i, which are random variables, each of them defined by a probability density function (PDF), assumed to be known. Using this model, we construct a polynomial chaos basis which is a sum of polynomials of the inputs θ_i. The coefficients of the sum are efficiently determined by projection. The interest of the PCE theory is to obtain statistical informations on the model response with limited computational effort. Indeed, once the PCE model is obtained, the coefficients of the sum are directly related to the statistics of the position estimate, such as the mean and the variance for instance.

To illustrate this approach, figure 4.14 shows the results of a positioning process simulated in Matlab. This scenario considers three anchors in the xy plane, whose locations are indicated by the blue circles. The AoA θ_i estimated by each anchor is defined by a Gaussian random variable, centered on the actual AoA, and of standard deviation respectively equal to 5°, 5°, and 1°. The black spot represents the actual UE position. Using the AoA θ_i of the three anchors and the PCE analysis, the UE position is estimated and represented by the black square. Performing a Monte-Carlo simulation over 20 000 realizations of θ_i, the 90% Confidence Region (CR) is plotted in figure 4.14 (see the black curve). This means that 90% of the 20 000 realizations led to an estimated position lying within this CR. This confidence region can be approximated in a much practical way using PCE, if the AoA PDF are known to the UE. Indeed, once the PCE basis has been determined, the mean and the variance of the position estimate are readily available using the PCE coefficients. Using those two first statistical moments and by assuming position coordinates x and y are uncorrelated, the 90% CR is plotted in figure 4.14 (see the blue dash curve). To improve the accuracy of this CR, the covariance between x and y is calculated and a principal component analysis is applied on it. This enables obtaining a rotated ellipse (see pink dashed line in figure 4.14) much closer to the actual CR, given by the Monte-Carlo simulation. So these results show that this method is able to closely approximate the confidence region of the device position and consequenly using PCE to perform positioning is a promising solution as in addition to estimated position, the system can also provide a measure of the uncertainty on that position if the PDF of the AoA of each anchors are know. This could in turn enable selecting which anchors are to be used in the localization process in order to improve accuracy.

Naturally, multiple factors are related to these AoA PDF such as mutual coupling between antennas, near-field scatterers in the vicinity of anchors, propagation channel effects, Signal-to-Noise Ratio... While some are deterministic effects (e.g., antenna mutual coupling) and could be somehow determined during a "calibration" stage, some others are time-varying (fading, SNR...) and can be estimated to some extent. The idea is therefore to find the relationships between those time-varying effects and the AoA PDF. This opens a large spectrum of perspectives for this work: how to estimate position uncertainties using channel estimation or any other available knowledge.

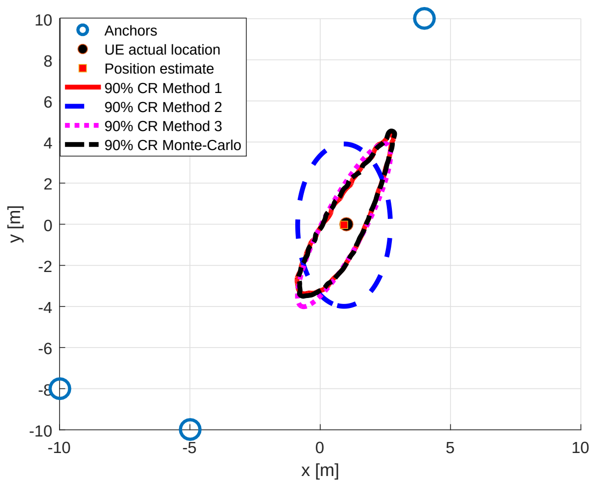
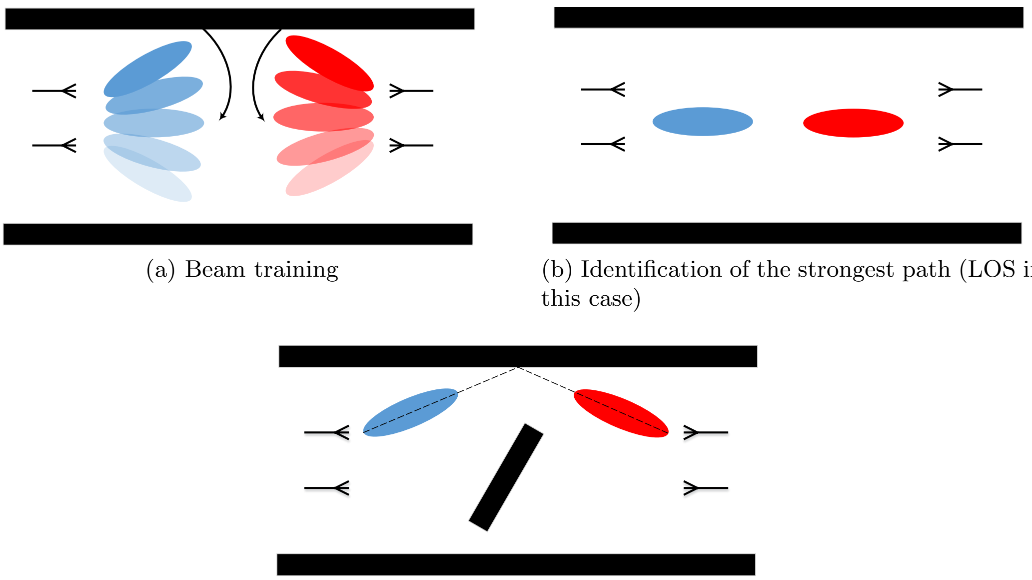


Figure 4.14: 90% confidence regions, obtained by different methods, and assessed by a Monte-Carlo calculation. The AoA standard deviations are 5°, 5° and 1°, respectively.

4.3.2 Localization in the 60 GHz band: shadowing and NLOS issues

At millimeter-wave frequencies, shadowing is a strong issue as waves do not travel through walls and humans for instance. Line-Of-Sight (LOS) blockage is therefore a common situation. When a LOS blockage occurs between a base station (BTS) and a User Equipment (UE), the communication can still operate thanks to a multipath. In this case, a beam training is considered, such as in the IEEE 802.11ad standard for indoor communications, where the BTS and the UE scan the entire room in order to find a Non-Line-Of-Sight (NLOS) channel, over which communicating. This scenario is illustrated in figure 4.15 where both BTS and UE are equipped with directional antennas and are looking for the strongest path (see figure 4.15a), which can be either a LOS (see figure 4.15b) or NLOS channel (see figure 4.15c). Depending on the UE capabilities, other situations consider only the BTS antenna to be directive, which makes the training easier but the link budget weaker. This NLOS path can be due to a reflection on a wall for instance. Performing localization based on this NLOS path leads to large position errors as any metrics (e.g., AoA, TDOA, etc.) estimated from this NLOS channel will not be strictly related to the UE position but also to the environment. Consequently, knowing whether the communication is based on a LOS or NLOS channel is an interesting feature to mitigate localization error or at least, to inform the system that the localization is not reliable (when based on NLOS channel). So we intend, with the PhD of Pengfei Lyu, co-supervised by Prof. Aziz Benlarbi-Delaï (L2E), Prof. Zhuoxiang Ren (L2E) and me, to investigate techniques in order to discriminate LOS from NLOS situations based on the channel estimation performed by 60 GHz communications. The idea being to help improving the localization process, but also to speed up the beam training by distinguishing whether a LOS path is lost during a communication because of a blockage or because the UE moves.



(a) Beam training

(b) Identification of the strongest path (LOS in this case)

(c) Identification of the strongest path (NLOS in this case)

Figure 4.15: Illustration of a beam training for 60 GHz communications with directional antennas.

A few studies conducted in the literature started tackling the issue of LOS/NLOS discrimination at frequencies below 10 GHz. The idea is to estimate statistical features from the channel estimated in time domain [58, 59, 60, 61, 62, 63, 64, 65, 66] or frequency domain [67, 68, 69, 70], to classify them according to known situations (i.e., LOS or NLOS in a learning process), and to use this classification in a real scenario. We intend to perform similar studies at 60 GHz where the bandwidth is very large and where statistical information related to multipath environments may be important, possibly leading to promising performance of LOS/NLOS detection. However, at 60 GHz a certain number of technologies use switched-beam antenna arrays instead of costly phased arrays. Indeed, analog solutions exhibit reduced hardware constraints with respect to digital ones that necessitate a digital/analog conversion at each antenna element to steer the radiated beam. However, with an analog switched-beam array, one does not have access to the transmitted/received signals of each antenna element in the array. Consequently, the channel estimation will be performed on a channel that includes the behavior of directive antennas, and

Conclusion

THIS HDR THESIS summarized the research I have conducted these past years along with different colleagues and students, and the research project considered for the coming years. My involvement in the activities related to teaching, administrative, and other non-purely-scientific aspects were also introduced.

While focusing on antennas and propagation, I have addressed different research areas including localization, antenna design, and channel modeling. Interestingly, the propagation channel has always played an important role in my work, and more specifically, the relation between channel and antenna upon the performance of a given scenario. For instance, the antenna behavior cannot be ignored while assessing MIMO capacity for a given channel, and in on-body communications, the antenna and the channel are so strongly coupled that it is simply not possible to separate their respective contribution to a given link budget for instance. In addition to this electromagnetic-oriented work, I have also been exposed to digital communications, both in simulations and in experiments, while working on the channel influence on localization or the assessment of on-off-keying modulations in body area networks. This diverse research background allowed me to propose the project detailed in Chapter 4, and more specifically the spatial data focusing approach. I showed that by acting on the digital modulation jointly with a multiple antenna system, we can overcome, for some scenarios, a classical limitation we encounter in the antenna field, namely, the relationship between beamwidth and aperture size.

Since I joined Sorbonne in September 2012, I have closely collaborated with multiple researchers from different places, including naturally Sorbonne and ULB, to whom I am thankful for the new skills I could acquire with them. These last years, along with my colleagues at L2E, we have obtained different fundings that have made possible expanding the available equipment and therefore establishing a suitable environment in terms of experimental ressources, which is a real strength for our laboratory. This will contribute to make our group known at a national and international level and this is also why, in the context of the merging between the L2E and the GEEPS laboratories, I actively participated to the creation of the "Wave and Propagation" group, involving 19 people, which we hope will create tight collaborations between researchers.

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