Université du Québec
Institut national de la recherche scientifique
Énergie, Matériaux et Télécommunications

Modeling and Analysis of Wireless Information and Energy Transmission in MIMO Systems

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

By
Gervais Nono Kamga

Evaluation Jury

Research Director	Prof. Sonia Aïssa INRS–Énergie, Matériaux et Télécommunications
External Examiner	Prof. Jean-François Frigon, École polytechnique de Montréal
External Examiner	Prof. Wessam Ajib, Université du Québec à Montréal
Internal Examiner	Prof. Douglas O'Shaughnessy

“What we can or cannot do, what we consider possible or impossible, is rarely a function of our true capability. It is more likely a function of our beliefs about who we are.”

Anthony Robbins

Abstract

The next generation of wireless communications systems are expected as a revolution in the area of telecommunications, where they promise tremendous network capacity, huge data rates for very high number of end users and simultaneous supported connections with large sensor deployments, as well as very high gains in terms of spectral efficiency, energy efficiency, latency, and coverage. To allow the emergence of such networks, it is necessary to satisfy the fundamental needs of available energy supply, and spectrum availability/efficient usage.

The wireless power transfer (WPT) techniques are shown to be strong, reliable with the potential to replace the currently-used yet painstaking wired charging; providing the end users with almost unlimited energy sources. Due the outstanding advantages these techniques promise, both academic world and the industry are actively investigating solutions for allowing networks to implement WPT, where the operating nodes can simultaneously harvest/transmit energy, while processing data signals. On the other hand, for solving the spectrum efficient usage/availability issue, improving the spectral efficiency has been extensively investigated through the several past years, and represents a very strong solution. In this regards, regular multiple-input multiple-output (MIMO) antenna technique, since the last decade, and, more recently, massive MIMO; have been widely exploited and are powerful wireless technologies for tremendously improving the spectral efficiency, and even energy efficiency.

Thanks to the above capabilities of regular- and massive MIMO, and of the WPT, these techniques have become strong candidates for the development and the emergence of the next-generation wireless communications networks. Considering that the theoretical understanding and practical deployment of these systems requires to first evaluate their performances, while taking into account various key propagation and networks characteristics; this thesis aims to provide a framework for channel

modeling and performance analysis of next-generation wireless communications networks, with information processing and energy harvesting, and implementing regular- and/or massive MIMO. More specifically, as a first step, in the initial part of the thesis, a generalized analysis for the spectral efficiency of both regular- and large-scale (massive) MIMO systems is performed, where major radio-propagation characteristics and antenna-array parameters are taken into account, including path loss, shadowing effect, multi-path fading, antenna correlation, antenna polarization, environmental cross-polarization coupling and antenna cross-polarization discrimination.

The second step of the thesis conducts the modeling and performance analysis of massive MIMO systems in terms of spectral efficiency, in both the centralized and the distributed configurations, referred to as centralized (C-MIMO) and distributed (D-MIMO), respectively. This is based on a novel comprehensive channel model, which accounts for real environmental parameters and antenna characteristics, namely, path loss, shadowing effect, multi-path fading and antenna correlation.

In the third part of the thesis, WPT is investigated. This is done by considering massive MIMO WPT systems, operating in millimeter wave (mmWave) bands; where both the rainy and non-rainy conditions are considered, and the channel model accounts for rainfall effects, path loss and fast fading. Then, finally, the fourth step of the thesis investigates the performance of networks with simultaneous energy harvesting and information transmission. The considered system implements massive MIMO, and operates in the mmWave bands, while accounting for rainfall effect, path loss and fading.

While conducting the work, the adopted methodology consists of modeling the channel, by considering major radio-propagation characteristics and antenna-array parameters; then conducting the performance analysis, in terms of the spectral efficiency (in the first two parts of the thesis), the harvested energy (in the third part), and the throughput (in the fourth part). These metrics are all derived in closed-form then studied in various key practical scenarios, to obtain important insights which are not only highly important for the comprehension of the different technologies in future networks, but will also benefit system designers and manufacturers in the design of these systems and their operating nodes.

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Contents

List of Acronyms

AF	amplify-and-forward
AP	access point
BS	base station
CSI	channel state information
C-MIMO	centralized
D-MIMO	distributed
HAP	hybrid data-and-energy access point
i.n.i.d.	independent but not necessarily identically distributed
LOS	line-of-sight
MIMO	multiple-input multiple-output
MMSE	minimum mean-square-error
mmWave	millimeter wave
NLOS	non-line-of-sight
PDF	probability density function
RF	radio-frequency
RV	random variable
Rx	receive
SISO	single-input single-output

SNR	signal-to-noise ratio
Tx	transmit
UE	user equipment
UHF	ultra high frequency
WEH	wireless energy harvesting
WIT	wireless information transmission
WPT	wireless power transfer
WSN	wireless sensor network
w.r.t.	with respect to
XPD	cross-polarization discrimination

Chapter 1

Introduction

1.1 Context and Motivations

The next generation of wireless communications networks, e.g. the future fifth generation (5G), promise outstanding advantages to be profitable for both the networks operators and the end users. These include an at least 1000-fold gains in network capacity, data rates of more than tens of Mbits/s (or Gb/s) for massive number of supported users, a capacity higher than hundreds of thousands of simultaneous and supported connections for massive sensor deployments, a spectral efficiency and energy efficiency increased by at least ten, a latency reduced significantly compared to current LTE, and a coverage that will be significantly improved. These features will help to face the exponential demand from users which number is always growing exponentially, improving both their access to networks, and the quality of the services they receive.

As always in the wireless communications, the new networks will have to meet two fundamental yet major challenges, in order to satisfy the very high requirements for the infrastructure systems: i) the energy supply which allows the networks operating nodes to power both their internal tasks and their data transmissions; and ii) the efficient usage of the (limited) wireless frequency spectrum.

In order to solve the energy supply issue in wireless communication systems, recently, wireless power transfer (WPT) techniques were shown to represent strong alternative to the currently-used wired charging, and will resolve the painstaking concerns of the shortage of battery endurance and the labour in the charging, encountered in the current cellular networks [1]. Because of this, and due to the tremendous advantages inherent to their use, WPT techniques are mobilizing important R&D interest worldwide.

With WPT, a relatively new trend consists of combining energy harvesting and information processing at the same nodes, where WPT/wireless energy harvesting (WEH) allow end users to wirelessly and remotely extract energy from either their received signal, the environment, or from energy sources such as power beacons. Thus, the wireless terminals can harvest energy from a wide range of almost always available energy sources, which is not the case with wired charging. Several applications already rely on the simultaneous use of WPT and information processing, see e.g. [2] for some examples.

On the other hand, for overcoming the challenge related to the spectrum availability, increasing the spectral efficiency is a must. The spectral efficiency indicates how efficiently a limited frequency spectrum is exploited, and increasing it yields and increase of the information rate that can be achieved over a given bandwidth, in a specific communication system. Since the last decade, multiple-input multiple-output (MIMO) antenna technique has established itself as a powerful wireless technology for improving spectral efficiency (and then higher data rates), and even better fault-tolerance capability, compared with single-input single-output (SISO) configurations. As a huge step further, massive MIMO communication technique, introduced in 2010 [3], where tens or a few hundred antennas are deployed at either or both ends of a wireless link, has the ability to dramatically improve the spectral efficiency. Moreover, massive MIMO also provides considerable gains in terms of energy efficiency, and even security and reliability compared with conventional MIMO [4] and, as demonstrated in some published works, using MIMO or massive MIMO in the simultaneous wireless information transmission (WIT) and WPT/WEH networks will contribute to significantly improve the system performance. For these reasons, massive MIMO is becoming a cornerstone of future 5G systems [4, 5].

1.2 Main Objectives and Work Steps

For theoretical understanding and practical deployment of the next generation of wireless communications networks in real propagation environments, where regular- or massive MIMO are considered along with/without energy harvesting; a prerequisite task is to perform modeling, as well as performance evaluation with respect to (w.r.t.) various key propagation and networks characteristics, where closed-form analysis is by far desirable, if not necessary. In this regards, the main objective of the present thesis is the modeling and understanding of potential performance of next-generation wireless communication networks, with information transmission and power transfer, under regular- and massive MIMO systems. For achieving this goal, the work was conducted through four main steps, summarized as follows.

- Information Transmission in Regular- and Massive MIMO Systems:
  In the initial main step, the starting point of the thesis; the objective is to investigate and understand deeply the information transmission in regular- and massive MIMO systems. To that end, in this step, a new and comprehensive channel model is first developed, and a generalized analysis for the spectral efficiency of both regular- and massive MIMO systems is conducted. Major radio-propagation characteristics and antenna-array parameters are taken into account, including path loss, shadowing effect, multi-path fading, antenna correlation, antenna polarization, environmental cross-polarization coupling and antenna cross polarization discrimination. In a first published paper [6], the proposed general and unified MIMO model is based on the very popular Kronecker model, where the aforementioned major environmental parameters and antenna physical parameters are taken into account; and the analysis is devoted to regular MIMO. Given that the Kronecker model does not allow spectral efficiency closed-form analysis, and presents some limitations regarding its accuracy (for more details, see Appendix B); a second paper was published [7], which exploits the Weichselberger method to reformulate the Kronecker model, yielding a new channel model which, although it is more complex, i) allows further closed-form performance analysis, and moreover; ii) benefits from the

accuracy of the Weichselberger method-based model. In the said second paper, the spectral efficiency analysis considers both regular- and massive MIMO.

- Information Transmission in Massive MIMO Systems under Centralized and Distributed Configurations:
  After understanding deeply the information transmission in both the regular- and massive MIMO and how their modeling and performance analysis work, in the second step of this thesis the purpose is to investigate the information transmission in massive MIMO systems, under both centralized and distributed configurations, referred to as C-MIMO and D-MIMO, respectively. By accounting for real environmental parameters and antenna characteristics, namely, path loss, shadowing effect, multi-path fading and antenna correlation, a novel comprehensive channel model is first proposed in closed-form, which is applicable to both types of MIMO schemes. Then, based on the proposed model, an exact analysis is conducted, where the asymptotic behavior of the spectral efficiency of the MIMO channel under the centralized and distributed configurations is derived and compared. Afterwards, a case study is performed by applying the obtained results into MIMO networks with circular coverage, where the subsequent findings shed new light on the design and deployment of massive D-MIMO systems in practice.

- Wireless Power Transfer with Massive MIMO in millimeter wave (mmWave) Bands:
  As outlined in the preceding section, simultaneous energy harvesting and information transmission is a highly important trend the wireless communication systems, given the associated benefits, and will occupy an important place in the next-generation wireless networks. Before addressing the simultaneous energy harvesting and information transmission topic, this thesis first focuses, in its third step, on the WPT/WEH, i.e. on a system model where only power transfer/energy harvesting is considered. Then, afterwards, the thesis addresses both information processing and power transfer/energy harvesting.

That is, this part studies the performance of WPT in massive MIMO systems, operating in mmWave bands, where both the rainy and non-rainy conditions are considered. By accounting for rainfall effects, path loss and fast fading, a comprehensive MIMO channel model is first developed, and is suitable for modeling the energy propagation in WPT mmWave massive MIMO systems. Then, by exploiting the law of energy conservation along with the theory of very long random vectors, the downlink energy transferred by energy transmitter (a hybrid data-and-energy access point (HAP)) and harvested by the user equipments (UEs) is analyzed, and studied in several important scenarios. This discloses several key results on the performance and the design of the considered system (see Section 2.3 below), which will not only be highly important for the comprehension of WPT in future networks, but will also benefit system designers and manufacturers in the design of these systems and their operating nodes.

- Simultaneous Wireless Power Transfer and Information Transmission:
  Finally, in the fourth and last step, this thesis performs the modeling and performance analysis of networks with simultaneous energy harvesting and information transmission, where massive MIMO is implemented. A dual-hop mmWave massive MIMO transmission system is considered, where a relay assists the long-distance communication between a source node and a destination node, with the relay being placed between the two nodes. The source node needs to first harvest energy, to be able to forward its data to the relay. A comprehensive MIMO channel model is first developed, where rainfall effects, path loss and small-scale fading are all considered, which properly models the signal propagation on all links of the system. The expressions of the asymptotic energy and power at the source are then derived, and help to assess the asymptotic spectral efficiency and throughput for various important scenarios. Further, the optimal value of the harvesting time that maximizes throughput is investigated. The obtained results show that, in light weather, the asymptotic spectral efficiency and throughput increase logarithmically with the number of relay antennas,

and that both metrics decrease exponentially with the rain parameters.

In the following content of this thesis, Chapter 2 presents a summary of the contributions achieved to meet the PhD project goals; and the full content of the papers included in the thesis are attached in Appendices A–F.

Chapter 2

Summary of Thesis Contributions

2.1 Information Transmission in Regular- and Massive MIMO Systems

As outlined in Chapter 1.2, in the initial main step of the thesis, which represents the starting point of the project, the main goal consists of investigating and understanding deeply the information transmission in regular- and massive MIMO systems. To achieve it, a new and comprehensive channel model is first developed, and a generalized analysis for the spectral efficiency of both regular- and massive MIMO systems is conducted.

2.1.1 Motivations and Literature Review

As outlined in the Introduction, for, among others, solving the spectrum scarcity issues in current and next generation of wireless communications networks; regular MIMO antenna technique guarantees a significant improve of the spectral efficiency, and massive MIMO promises much better performances.

Before it is possible to deploy either regular- or massive MIMO systems in practical multiusers systems, the most fundamental task is to theoretically analyze and understand the performance of these networks in the point-to-point setting.

Such performance analysis and evaluation requires the consideration of not only natural environmental parameters but also antenna physical parameters, where the latter is particularly crucial to massive MIMO. In fact, compared to conventional MIMO systems, the limited size of transmitters/receivers makes an effective separation among multiple antennas hard to achieve and, thus, antenna polarization technology is widely believed to be a promising technique in deploying large-scale MIMO in practice. Even so, the correlation among antennas with the same polarization is still inevitable. Therefore, developing analytical MIMO channel model encompassing natural environmental propagation parameters and antenna physical ones is the cornerstone for the design and performance analysis of large-scale MIMO in practice. Nevertheless, such a general modeling that admits mathematical tractability is far from straightforward, due to the numerous parameters involved, needless to say the extremely high analytical complexity with respect to key channel statistics, such as outage probability and spectral efficiency. In general, environmental parameters mainly include path loss, shadowing effect, multipath fading, and environmental cross-polarization coupling, while antenna parameters generally deal with antenna polarization, antenna correlation, and antenna cross-polarization discrimination (XPD).

In the open literature, numerous publications were devoted to analyzing the spectral efficiency of MIMO systems w.r.t. various channel models, where, however, each of the existing MIMO models is devoted to a specific scenario. Among these models, the most basic one accounts for multi-path fading only, such as Rayleigh and Ricean fading, where in both cases, the channel statistics are jointly Gaussian and the performance analysis can be conducted by using the well-known Wishart matrix theory [8]. The Nakagami fading model, known to more accurately describe real propagation environments, and encompassing Rayleigh and Rice as special distributions, was exploited in [9] to analyze the spectral efficiency of MIMO systems where, due to high difficulty of mathematical tractability, some bounds were proposed. As a step further, a model addressing the joint effect of multi-path fading, shadowing and path loss, was reported in [10]. More recently, [11] considered the basic Rayleigh fading along with correlation, in conjunction with shadowing effect and path loss, for studying the so-called distributed MIMO systems. In [10] and [11], the system performances were studied by means of bounds on the spectral efficiency.

On the other hand, to address the challenges related to antenna correlation and the limited size of transmitters/receivers where effective separation between antennas is hard to achieve, antenna polarization technology was extensively applied, yielding the polarized MIMO channel models. For instance, the co-located orthogonally-polarized antenna configuration was already shown to be a space- and cost-effective solution in practice [12]. Based on this model, performance of MIMO transmission with polarization diversity was analyzed in the context of Rayleigh and Ricean fading [13–15], and the Loo propagation model [16].

2.1.2 Major Contributions

For ease of mathematical tractability, each of the aforementioned MIMO works, however, considers only specific scenarios, where some environmental or antenna physical parameters are ignored. Even the MIMO spatial channel model recommended by the 3rd Generation Partnership Project (3GPP), is presented by means of computer algorithm without closed-form performance metrics, hindering the development of advanced network management policies [17]. It goes without saying that, a general analysis applicable to most popular scenarios and accounting for major physical parameters in practical deployment is not only imperative, it is also necessary for a unified closed-form performance evaluation of realistic MIMO systems.

Aiming at a framework for unified performance evaluation of MIMO systems, this part of the thesis analyzes the spectral efficiency of both regular- and massive MIMO configurations, based on a general channel model where major environmental and antenna physical parameters, including path loss, shadowing effect, multi-path fading, antenna correlation, antenna polarization, environmental XPC and antenna XPD, are all accounted for. More specifically, this part of the project is subdivided into two works, published through [6] and [7], where, due to the extremely high analytical complexity involved in closed-form performance evaluation based on the comprehensive model, the analysis is conducted in terms of upper bound on the spectral efficiency.

To the best of my knowledge, no prior work in the open literature comprehensively considered the said propagation and antenna parameters all together, for conducting a unified closed-form performance analysis of regular- and/or massive MIMO systems, as detailed in my published papers [6] and [7].

Despite [9] and [10] where an upper bound on the spectral efficiency of regular MIMO systems was investigated, four major contributions of this work are summarized as follows.

General and Unified Channel Modeling for Regular/Massive MIMO

A general and unified channel model is first developed, where major radio-propagation characteristics and antenna-array parameters are taken into account, including path loss, shadowing effect, multi-path fading, antenna correlation, antenna polarization, environmental cross-polarization coupling and antenna cross-polarization discrimination.

- In the first work [6], the proposed channel model exploits the very popular Kronecker correlation model, to account for the antenna correlation, which is severe in large-scale MIMO configurations, as highlighted above. The obtained general and unified dual-polarized MIMO channel model, is given by

  $$\mathbf{H} = d^{-\frac{\nu}{2}} \varphi^{\frac{1}{2}} \, \mathbf{\Theta}_R^{\frac{1}{2}} \, \widehat{\mathbf{H}} \left(\mathbf{\Theta}_T^{\frac{1}{2}} \right)^{\mathrm{H}} \otimes \mathbf{X}, \tag{2.1}$$

  where the operator $\otimes$ denotes the Kronecker product, d denotes the distance between the transmitter and the receiver, ν the path-loss exponent, φ the shadowing component of the channel, α and Ω_{s} the shadowing parameters, $\widehat{\mathbf{H}}$ the multipath channel matrix, m and Ω_{f} the multi-path fading parameters, and $\mathbf{X} \in \mathcal{R}^{2\times 2}$ represents the fading power leakage matrix.

  More elaborate details about the channel modeling with the Kronecker model is given in Section II of the paper attached in Appendix A below.

- In the second work [7], the Weichelberger method is exploited to reformulate Kronecker correlation model, so that the obtained channel model allows closed-form analysis. In fact, the channel model in the form of (2.1) does not necessarily allow closed-form spectral-efficiency analysis. As an alternative, the Weichselberger method is exploited to reformulate the Kronecker model involved in (2.1), yielding a new yet tractable channel model. The obtained Weichselberger method-based model, in addition to enabling further closed-form analysis, offers a better accuracy compared with the Kronecker model which, though it is by far the most popular correlation model used in conventional MIMO systems, suffers some limitations. In particular, the Kronecker model describes the MIMO channel by the separated correlation properties of both link ends and then neglects the joint spatial structure, whereas the Weichselberger method-based model accounts for mutual dependence of the correlation at both link ends, and describes the coupling from the transmit (Tx) eigenmodes to the receive (Rx) eigenmodes. One consequence is that the Kronecker model may underestimate the channel capacity of large-scale MIMO systems, since it does not render correctly the multipath structure of the channel. In particular, compared to the Weichselberger method-based model, measurements demonstrated that the Kronecker model shows important deficiencies when the MIMO system operates with, e.g., more than 8 antennas at both link ends [18], [19]. Moreover, a measurement campaign conducted for a multi-user massive MIMO configuration, proved significant underestimation of the system capacity due to the use of the Kronecker model [20]. For instance, [20] reported some degradations related to the use of the Kronecker model (compared to channel measurements), of 9%, 15% and 18%, for respectively 5, 32 and 128 antennas at the base station. A comprehensive comparison of the Kronecker and Weichselberger models can be found in [21, Section 2.3.1].

By exploiting the Weichselberger method-based model, and after lengthy algebraic manipulations, a new general and unified dual-polarized MIMO channel model is obtained, where all the aforementioned channel and physical parameters are considered. The said model is given as

$$\mathbf{H} = d^{-\frac{\nu}{2}} \varphi^{\frac{1}{2}}\, \mathbf{U}_R^{\frac{1}{2}} (\mathbf{G} \odot \widehat{\mathbf{H}}) \left(\mathbf{U}_T^{\frac{1}{2}}\right)^{\mathrm{H}} \otimes \mathbf{X}, \tag{2.2}$$

where d, ν, φ, α, Ω_{s}, $\widehat{\mathbf{H}}$, m, Ω_{f} and $\mathbf{X}$ are as defined right after (2.1) above, whereas $\mathbf{U}_T^{\frac{1}{2}}$ and $\mathbf{U}_R^{\frac{1}{2}}$ are the Weichelberger method matrices (that are obtained respectively from Tx and Rx correlation matrices).

Remark 1 (Special cases of the two proposed general MIMO channel models) With the resulting expressions (2.1) and (2.2), by altering the values of path-loss exponent (ν), shadowing parameters (α and Ω_{s}), multi-path fading parameters (m and Ω_{f}), the power leakage matrix ($\mathbf{X}$), correlation matrices $\mathbf{\Theta}_T$ and $\mathbf{\Theta}_R$ (for (2.1)) and the Weichelberger method matrices $\mathbf{U}_T^{\frac{1}{2}}$ and $\mathbf{U}_R^{\frac{1}{2}}$ (for (2.2)), various types of MIMO channels reported in the open literature can be easily described.

Analytical Results and Key Results

In both works [6] and [7], after the channel modeling, an upper bound on the spectral efficiency is derived in the subsequent analysis, and is afterward studied to obtain various insights onto the system performances. In this regards, [6] focused on the large-scale MIMO systems, while [7] investigates the spectral efficiencies of both regular- and massive MIMO. More specifically:

- In [7], based on the general MIMO model developed by exploiting the Weichselberger method as mentioned above, an upper bound on the spectral efficiency of the channel is derived. To this end, a target matrix $\mathbf{M}$, expressed w.r.t. the Weichselberger method parameters, is first used to reformulate the original expression of the instantaneous spectral efficiency. Then, the probability density function (PDF) of the diagonal entries of $\mathbf{M}$ is derived. Afterwards, the resulting PDF is applied to attain the desired upper bound, by using the Hadamard's determinant inequality for positive semi-definite matrices. In particular, the orthogonally-polarized antenna configuration that can be used to double the number of antennas on a given array, without extending the array geometric size, is confirmed to be a good candidate for the implementation of practical massive MIMO systems.

- The aforementioned upper bound is further analyzed in the high signal-to-noise ratio (SNR) regime. Compared with the high-SNR analysis conducted in [9, 10], the PDF of some intermediate random variables (RVs) is derived prior to obtaining the asymptotic expression of the spectral efficiency. This reveals, explicitly and simply, the impact of various system parameters on the spectral efficiency. For instance, the spectral efficiency is shown to increase faster w.r.t. the fading severity parameter, than w.r.t. the shadowing severity parameter.

- Further, the asymptotic behavior of the spectral efficiency in the sense of massive MIMO is analyzed (note that massive MIMO analysis is not performed in [9, 10]). Accordingly, several key insights into the system performance are gained. In particular, the obtained result shows that the system performance of massive MIMO is mainly determined by the correlation characteristics at the end with fewer number of antennas, given that the Weichselberger method-based correlation model is applied. Also, when the numbers of Rx and Tx antennas (denoted N_R and N_T, respectively) increase at the same rate, i.e., $\kappa \equiv N_R/N_T < \infty$, it is disclosed that the spectral efficiency of massive MIMO increases logarithmically with κ if $N_R > N_T$, whereas it is independent of κ if $N_R \leq N_T$.

Thanks to their high generality, the channel models and the analyses developed in [6] and [7] for this part of the thesis, which are corroborated by Monte-Carlo simulation results, benefits system designers in the design and performance evaluation of either regular- or massive MIMO systems while accounting for realistic phenomena characterizing both the propagation environment and the antenna arrays.

More details (e.g. mathematical tools and methodology) regarding the analysis of the spectral efficiency and the obtained results, can be found in [6, Sections III, IV] and [6, Appendix A] (for large-scale MIMO systems), and [7, Sections III–V] and [7, Appendices A–C] (for both regular- and large-scale MIMO). The works [6] and [7], which are appended in Appendices A and B, respectively, were respectively published in Proceedings, IEEE International Conference on Communications 2015 conference, and in the IEEE Transactions on Vehicular Technology journal.

2.2 Information Transmission in Massive MIMO Systems under both Centralized and Distributed Schemes

As outlined in Chapter 1.2, after understanding deeply the information transmission in both the regular- and massive MIMO and mastering the technical tools used for modeling and performance analysis in these networks, in the second step of this thesis the purpose is to investigate the information transmission in massive MIMO systems, under both centralized and distributed configurations, referred to as C-MIMO and D-MIMO, respectively. At this stage of the thesis, the purpose is also to further master the technical tools required to perform the modeling and performance analysis of massive MIMO systems.

2.2.1 Motivations and Literature Review

By recalling the highly important role of massive MIMO in the next generation of wireless networks, and following the above two works achieved in the first step of the thesis, where regular- and large-scale MIMO are considered; this part of the project aims to develop a channel model and provide a framework for unified performance evaluation of massive MIMO systems, where the developed channel model is general and accounts for major environmental and antenna physical parameters.

To implement massive MIMO in wireless networks, two different schemes can be adopted (see, e.g., [22–24]): centralized (C-MIMO), where antennas are co-located at both the Tx and the Rx sides as illustrated in Fig. 2.1-a (which is essentially equivalent to conventional MIMO system), and distributed (D-MIMO), where base station (BS) antennas are deployed at different geographical locations while connected

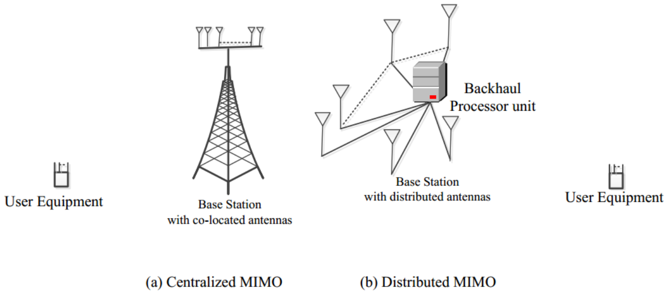

Figure 2.1: Two configurations of point-to-point massive MIMO systems: (a) C-MIMO, where antennas are co-located at the BS and the UE sides and, thus, distances from UE to BS antennas are almost identical; (b) D-MIMO, where BS antennas are deployed at different geographical locations while connected together through the backhaul processor unit, implying that the distances from UE to BS antennas are different.

together through high-capacity backhaul links such as fibre-optic cables, as shown in Fig. 2.1-b.

From a practical point of view, C-MIMO is more easy to mathematically analyze and physically deploy, compared with D-MIMO. In fact, unlike the former, the latter suffers from different degrees of path losses caused by different access distances to different distributed antennas, which makes the performance analysis and design more challenging. Also, since the location of antennas in D-MIMO has a significant effect on the system performance, optimization of the antenna locations is crucial [23, 25]. This task may become very challenging because of the large (massive) numbers of Tx/Rx antennas. On the other hand, in practice, arbitrary antenna locations or optimal topology may lead to a prohibitive cost for the backhaul component, as well as installation cost for the distributed setting.

D-MIMO technique, however, exhibits several advantages compared with C-MIMO, such as lower transmit power, higher multiplexing gain, higher spectral efficiency, enhanced coverage area and ease of network planning [26, 27]. As such, both C-MIMO and D-MIMO represent promising choices for practical implementation of massive MIMO technique, each depending on potentially preferable criteria mentioned above.

No matter whether the centralized or distributed configuration is concerned, to capture the propagation characteristics and to understand the system performance and behaviour in real physical environments, two fundamental tasks are to i) develop an analytical channel model, where path loss, shadowing effect and multi-path fading are accounted for; and to ii) conduct analytical performance evaluation and assess key factors that determine system performance. In particular, for D-MIMO systems, different path losses and shadowing effects w.r.t. different BS antennas are critical to the realization of Tx/Rx diversity. In addition, antenna correlation is inherent to the realization of massive MIMO, because of the lack of sufficient physical space to separate the large number of antennas in case they are co-located.

In practice, the performance of point-to-point massive MIMO serves as a benchmark for further performance evaluation in multi-user settings. Also, point-to-point massive MIMO finds wide applications, e.g., high-speed wireless backhaul link between BSs [28]. However, despite the extreme importance of point-to-point massive MIMO, there is no existing work that successfully accounts for all the aforementioned parameters (i.e., path loss, shadowing effect, multi-path fading and antenna correlation), while developing channel model and conducting closed-form performance analysis. In particular, it was shown in [29] that for MIMO channels, the spectral efficiency grows linearly with the minimum between the numbers of Tx and Rx antennas, even if they tend to infinity. The asymptotic result when the number of antennas at only one side goes to infinity was reported in [30, 31]. In [29–31], only basic multi-path fading was considered whereas path loss, shadowing and antenna correlation were ignored. In [32–34], the capacity of correlated multi-antenna channels was studied, in both regimes of finite numbers of antennas (in [32]) and large numbers of antennas (in [32–34]), where only the Rayleigh fading and the antenna correlation were considered. As presented above, in my works [6] and [7], a comprehensive channel model consisting of path loss, shadowing, multi-path fading, antenna correlation and polarization was firstly developed. Then, an upper bound on the ergodic capacity of point-to-point C-MIMO was derived, by using the Hadamard's determinant inequality, and further asymptotically analyzed in the sense of larger number of Tx and/or Rx antennas.

2.2.2 Key Differences with the Previous 2 Works

Between my previous works [6] and [7] and the work conducted in this part of the thesis, two major differences are:

a) System model: Only C-MIMO is considered in [6] and [7] whereas C-MIMO and D-MIMO are jointly studied in the work conducted in this part of the thesis. In particular, the major contribution of the latter work is pertinent to D-MIMO.

b) Analysis methodology: In [6] and [7], an upper bound on spectral efficiency capacity is analyzed in the sense of larger number of Tx and/or Rx antennas, by using the Hadamard's determinant inequality. Instead, in the work conducted in this part of the project, exact spectral efficiency is first derived and then analyzed in the sense of large number of Rx antennas, by using the theory of very long random vectors.

2.2.3 Major Contributions

General C-MIMO and D-MIMO Channel Modeling

By accounting for real environmental parameters and antenna characteristics, namely, path loss, shadowing effect, multi-path fading and antenna correlation, a novel comprehensive channel model is first proposed in closed-form, which is suitable for both massive C-MIMO and D-MIMO. As apposed to the Kronecker correlation model used in [6], this work uses the Weichselberger model exploited in [7], and which is more accurate than the former as detailed in the previous chapter. Moreover, although various parameters needed in channel modeling have been partially considered to some extent in the open literature, key channel parameters, namely, path loss, shadowing, multi-path fading and antenna correlation, are concurrently taken into account and their effects on spectral efficiency are investigated in this work.

Asymptotic Analysis and Key Results

- Based on the proposed channel model, the asymptotic behavior of the spectral efficiency of the MIMO channel under the centralized and distributed configurations is analyzed and compared in exact forms, in the sense of large number of Rx antennas, by exploiting the theory of very long random vectors. More specifically:
    a) The law of large numbers for very long random vectors with independent but not necessarily identically distributed (i.n.i.d.) entries is first extended, to the more general case of very long random vectors with weighted i.n.i.d. entries, where a condition is imposed onto the weights to guarantee the convergence in probability.
    b) Then, two target matrices are introduced in the expressions of the spectral efficiency: $\mathbf{M}_{\mathrm{C}}$ for C-MIMO and $\mathbf{M}_{\mathrm{D}}$ for D-MIMO. Afterwards, the above results on the law of large numbers for very long random vectors with weighted i.n.i.d. entries are exploited to explicitly derive the asymptotic expressions of the entries of $\mathbf{M}_{\mathrm{C}}$ and of $\mathbf{M}_{\mathrm{D}}$, with respect to the number of Rx antennas N_R where $N_R \rightarrow \infty$.
    c) The resulting asymptotic behavior is then applied to derive the intended spectral efficiency, which yields novel expressions from which several new insights into the system performance can be gained. In particular, the obtained results show that, i) D-MIMO does not always outperform C-MIMO in terms of spectral efficiency; ii) D-MIMO exhibits a higher multiplexing gain than that of C-MIMO, up to $N_T \times N_R$ where N_T denotes the number of Tx antennas; and iii) the performance of massive MIMO on the uplink is mainly determined by the correlation characteristics at the Tx side instead of the Rx side, given that the Weichselberger correlation model is applied.
- A case study is performed by applying the obtained results in a pertinent scenario where the design of the D-MIMO adopt a circular topology, and several key insights into the system performance and optimal antenna deployment are

gained. In particular, it is demonstrated that for D-MIMO with circular topology of cell radius r_c and circular antenna array of radius r_a, the optimal value of r_a that maximizes the average spectral efficiency is given by $r_\mathrm{a}^\mathrm{opt} = r_\mathrm{c}/1.31$.

The proposed comprehensive channel model, the developed analysis and the obtained results, thanks to their generality and compactness, can serve as practical benchmark for designing and analyzing performances of massive MIMO systems in real physical propagation environments.

More details regarding the channel modeling, the spectral-efficiency analysis and the obtained results, can be found in [35, Sections II–V] and [35, Appendices A–E]. This work [35], which is appended in Appendix C, was published the IEEE Transactions on Communications journal.

2.3 Wireless Power Transfer in mmWave Massive MIMO Systems

As highlighted above, WPT/WEH techniques are of high importance for the next-generation wireless communications networks, where they will occupy a place of choice. On the other hand, massive MIMO technique, studied in the previous part of the project, can hugely improve the performances of power transfer, in the wireless communications networks. After the deep understanding of information transmission in massive MIMO systems, as well as the technical tools for modeling and understanding of performance of these systems; the rest of the thesis is devoted to WPT and information transmission. Prior to WEH and information transmission topic, in this part of the thesis, the modeling and performance analysis of WPT in mmWave massive MIMO systems, are first addressed.

2.3.1 Motivations and Literature Review

Conventionally, wireless devices, in e.g. cellular systems and wireless sensor networks (WSNs), are powered by batteries which, once their stored energy is depleted or at critical levels, have to be manually recharged or replaced. Wired charging, which is currently the main way to supply wireless devices batteries, is a compulsory but painstaking routine, and can even be a major issue in many cases. For instance, if the device battery cannot be recharged when and where needed, an abrupt service interruption will not only yield poor quality of experience, but can also lead to dramatic losses, e.g. critical data in sensitive applications or even lives in emergency situations. Even when backup batteries are available, frequent battery replacement is a daunting task and inconvenient (e.g. in large-scale WSNs), costly, sometimes dangerous (e.g. in access-prohibited/dangerous areas) or even impossible (e.g. in implanted medical devices) [36].

As an alternative, WPT techniques are very promising. Recently, they have drawn a significant R&D interest due to their potential to provide unlimited power supplies to wireless devices through energy collection from more continuously available sources. Current WPT technologies can be classified into two categories, depending on the physical mechanisms they employ, namely, magnetic resonant coupling and electromagnetic radiation.[1] This work falls in the latter category, i.e. radio-frequency (RF) based WPT, in which the radiative far-field properties of the electromagnetic waves are exploited such that a power receiver could harvest energy remotely from the RF signals radiated by a transmitter [36,37]. RF-based WPT presents many practical advantages compared with magnetic resonant coupling, such as longer operating range, lower production cost, and smaller Rx form factor [36].

The idea of magnetic resonance and/or RF based far-field power transfer techniques are not new, rather, it dates back to the late 1800s. Heinrich Hertz, in 1887 [38, Fig. 24], demonstrated the earliest prototype of magnetic resonance based WPT. An attempt to wirelessly transmit power at Colorado Springs, CO, USA, was conducted in practice, by Nikola Tesla, in 1899. However, no data were collected during this experiment, on whether any significant amount of power would be available at any distant point. The first power transfer that was successfully performed,

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[1] By recalling that in inductive coupling the Tx/Rx distance cannot exceed few centimeters, this near-field wireless power charging technology is not adapted to face either the concern on the shortage of battery endurance or the labour in the charging [1].

was the Harrell V. Noble at the Westinghouse Laboratory, which was demonstrated to the general public at the Chicago World's Fair of 1933–1934 [39]. Then, Lav R. Varshney, in 2008, at MIT, proposed for the first time to transport power and data simultaneously in wireless communication systems [40].

Currently, in practice, WPT finds many applications. For instance, it is highly useful in energy-constrained WSNs that are employed in, e.g., intelligent transportation, structural monitoring and intrusion detection [41]. Also, WPT can be used for charging low-power devices such as temperature and humidity meters, and liquid crystal displays [42]. It is even possible to use WPT in low-end computation, sensing and communication applications [43].

Though tremendous advantages are promised by WPT techniques, important issues need to be addressed before they can be implemented in the next generation of wireless communication networks. Firstly, due to the high attenuation of the electromagnetic waves over distance, only a small fraction of the energy radiated by an energy Tx can be harvested by the energy Rx, which can severely limit the range of WPT [1, 44]. Secondly, unlike information transfer where the sensitivity of the information Rx is around -60 dBm, in WPT, the sensitivity of a typical energy Rx is up to -10 dBm [36]. Thirdly, another serious issue with WPT is the energy transfer/harvesting efficiency, especially since the sensitivity of current energy Rx is not good, compared to, e.g. information receivers.

To meet these issues and realize WPT in practice, two main solutions consist in i) concentrating the RF energy into narrow beams, known as energy beamforming [45]; and ii) from a network design perspective, making the distance between the energy Tx and the energy Rx as small as possible. More recently, massive MIMO was shown to be highly attractive for improving the performance of WPT, with tremendous advantages promised. In fact, a recent investigation on the "feasibility of WPT using massive MIMO antenna arrays" revealed several important gains [2].

On the other hand, mmWave communication paradigm, which is a prime candidate for future 5G networks, offers all the three key solutions discussed above for boosting the performance of WPT, i.e. i) highly directional RF waves, ii) shorter distances between access points (APs) and UEs, and iii) large number of antennas at the APs.

Indeed, recent research advances support that mmWave systems will typically operate with directional beamforming at the Tx/Rx using very large antenna arrays, and a dense deployment of APs for a coverage comparable to operation at ultra high frequency (UHF) [46]. Clearly, these mmWave design characteristics are attractive for far-field energy transfer, and can significantly boost the performance of WPT systems.

However, the signal propagation at mmWave frequencies is subject to severe impairments, which could affect the energy transfer significantly. First, mmWave signals are sensitive to blockage, as they suffer poor penetration and diffraction [47, 48]. Another major impediment to mmWave signals is their high sensitivity to weather conditions, specifically to the attenuation due to rain. Severe rain such as heavy rain, downpour (e.g., in the U.S.) and monsoon (e.g., in south China) can even interrupt mmWave communications [49]. In current UHF cellular systems, below 6 GHz, rainfall effect is generally considered as a uniform propagation attenuation during link planning [47, 48]. This approach is accurate in these systems where the typical diameter of rain drop is much smaller than the signal wavelength [50]. In mmWave systems, a completely different approach is necessary. In fact, since the wavelengths of mmWave signals are comparable to the rain drop size, these signals suffer severe absorption and scattering when transmitted through rain and, consequently, severe amplitude attenuation and phase fluctuation [51].

In regards of the discussions above, several questions need to be answered as per the potential gains of WPT over mmWave frequencies: (1) What is, in terms of improving the harvested energy at a UE, the potential gain from using massive MIMO in mmWave WPT when there is no rain? More specifically, what are the scaling laws that arise from the use of large antenna arrays in mmWave WPT in non-rainy operating conditions? (2) In raining weather, on the other hand, which losses the WPT process would encounter, and how does the harvested energy decrease with the rain rate? (3) When rain parameters increase by a certain factor, thus meaning heavier rain, what are the number of antennas and/or level of downlink transmit power necessary to retrieve the initial value of the harvested energy before the degradation in the raining conditions? (4) When energy Rx is mobile, and its distance from the energy Tx varies randomly, what is the average energy it can harvest over time, and what are the impacts of the number of antennas and the rainfall on the harvested energy? (5) In terms of network design, which parameters can be altered and how to do so in order to compensate (or diminish) the rainfall effect, or simply increase the WPT performance when there is no rain?

This part of the thesis answers these questions in a comprehensive study, and provides a tractable framework to characterize the performance of WPT in future mmWave networks with or without rain attenuation.

As aforementioned, important gains from using massive MIMO in WPT systems were recently highlighted in [2, 52–55]. Even though analytical expressions for the harvested energy in massive MIMO systems are provided in [52–55] (but not in [15]), all these works apply only to the UHF bands. That is, closed-form analysis of the harvested energy with massive MIMO and the subsequent scaling laws, in mmWave bands, are not yet performed. More recently, [56] and [48] investigated WPT in mmWave band and concluded that substantial gain can be achieved over lower frequency solutions. Contrary to our present work where energy scaling laws w.r.t. the number of antennas are derived, the focus of [56] and [48] was on finding the energy coverage probability, with help of stochastic geometry tools, for cases where a device extracts either energy solely or energy and information from the mmWave signals. Further, and to the best of our knowledge, none of the existing papers in the open literature have yet analytically considered the rainfall effect in the performance evaluation of WPT systems, as conducted in this work.

For achieving the purpose of this part of the thesis, where the above-mentioned questions are all answered, the work is conducted through two papers: the first one [57], published as a paper conference (see Appendix D for the detailed contents) in Proceedings, IEEE International Conference on Communications 2017 conference, and the second one [58], which generalizes the work in [57], accepted for publication in the IEEE Transactions on Communications journal.

Compared with existing works, the major contributions of this part of the thesis are summarized as follows:

2.3.2 Major Contributions

mmWave MIMO Channel Modeling

A comprehensive channel model suitable for modeling the energy propagation in mmWave massive MIMO WPT systems is developed; where rainfall effect, path loss, and small-scale fading (line-of-sight (LOS) and non-line-of-sight (NLOS)), are all considered. While the inclusion of rain parameters is based on [50], i) our work considers the path loss, which is neglected in [50] although highly critical; and ii) the LOS propagation matrix as well as the NLOS propagation matrix are developed in a different way.

Performance Analysis and Key Results

- The channel matrix, which is unknown at the HAP, is estimated. For such, we exploit the minimum mean-square-error (MMSE) channel estimation properties. In particular, the pilot sequences sent by the UEs to the HAP, the corresponding length and transmit power, as well as all the channel propagation characteristics, are accounted for. The developed framework is useful for estimating the channel matrix in mmWave MIMO WPT systems, with or without rainfall.

- Analytical results on the estimated channel matrix are obtained. These include i) the explicit expression for the entries of the estimated channel matrix, ii) the conditional correlation matrix of each column, iii) the conditional square of the inner product of a column by itself, iv) the inner product of a column by itself and the corresponding mean, and v) the inner product of any two distinct columns and its corresponding mean. Besides allowing further analysis, our results on the estimated channel matrix allow for obtaining various analytical results like the ones mentioned in points i–v, for different scenarios, including perfect/imperfect channel state information (CSI) and rainy/non-rainy conditions.

- The downlink energy transferred by the HAP and harvested by the UEs is analyzed, and studied in important scenarios. Specifically,

  a) By exploiting the law of energy conservation, we first express the harvested energy at each UE w.r.t. the beamforming vector, the WPT time slot length, the HAP transmit power and the harvesting efficiency. The expected value of the harvested energy is further decomposed, to facilitate subsequent analysis.
  b) The analytical results derived above are applied to the said decomposition to derive the asymptotic harvested energy at each UE, in the sense of large number of HAP antennas (M). This yields novel expressions from which new insights into the system performance can be gained. In particular, it is shown that i) the energy harvested by each UE is a linearly increasing function of the number of HAP antennas. In the context of massive MIMO, this promises significant energy gains especially in light rain conditions and when path loss is not too high. The obtained scaling law also shows that in light rain conditions, the HAP transmit power can be reduced significantly to satisfy the regulations w.r.t. human safety. It is also shown that iii) the harvested energy decreases exponentially with the rain parameters (absorption coefficient τ_{a}, and optical depth τ_{o}) which increase with the operating frequency. Given the high values of τ_{a} and τ_{o} in certain cases, rain attenuation can significantly impact the WPT in mmWave systems and/or make it impossible in some scenarios, regardless of the value of M. Besides, c) Reference case studies are investigated including i) perfect CSI, ii) non-rainy conditions, and iii) perfect CSI with no rain. For instance, it is shown that when there is no rain, the asymptotic harvested energy no longer depends on channel estimation and still depends on path loss.

- To understand how far severe rain can affect the performance of WPT in mmWave massive MIMO systems, further analysis is performed to answer the following question: in case the rain parameters increase by a certain factor, how much the HAP number of antennas and the transmit power need to be so as to retrieve the initial value of the harvested energy before the said increase? To this end, two new factors are introduced in the analysis: the rain increase factor quantifies the increase of the rain parameters, and the retrieval factor gives an idea about by how much the number of antennas or the transmit power should be multiplied to retrieve the initial value of the harvested energy.

- The obtained results are applied in a pertinent scenario where UEs are randomly located around the HAP. The average harvested energy is derived, which shows what is, on average, and in all the studied scenarios pertaining to the points above, the amount of harvested energy at each UE. The results reveal that for a WPT network with coverage radius R_{n} and exclusion radius R_{e}, a significant increase in the average energy can be achieved by decreasing R_{e} and R_{n} (where this increase is more important w.r.t. R_{n} compared to R_{e}), which confirms that small-cell configurations (e.g. microcells and picocells) create a suitable platform for enhancing the WPT performances in mmWave massive MIMO networks.

As mentioned above, this work was divided into two parts, the first one is published in the Proceedings of IEEE International Conference on Communications 2017 (and appended in Appendix D); and the second one (appended in Appendix E) is accepted for publication in the IEEE Transactions on Communications.

2.4 Modeling and Analysis for Simultaneous WPT and WIT in mmWave Massive MIMO Systems

As the final stage of this thesis, and to achieve its main goal, this part of the project addresses the modeling and performance analysis of networks with simultaneous wireless information transmission and power transfer, in mmWave massive MIMO systems.

A dual-hop transmission system is considered, where the communication between a source node (S) and a destination node (D) is assisted by a relay node, placed between S and D, and where the amplify-and-forward (AF) protocol is implemented.

2.4.1 Motivation and Literature Review

Besides energy supply, another major issue in wireless communications is the severe signal attenuation w.r.t. distance, due to path loss and/or obstacles on the path between the transmitter and the receiver. To address this concern, relaying techniques, where one or several relays located between the transmitter and its end receiver assist their communication, has been widely adopted in the RF communication networks. To take advantage of the significant benefits obtained through the use of relays in wireless communications systems, researchers recently adopted the relay concept in networks where both WIT and WPT take place, see e.g. [59–62]. In these works [59–62], the relay needs to extract energy from the signal received from the source node in order to forward that signal to the destination node.

On the other hand, and as highlighted through the above parts of this thesis, in the context of the next generation of wireless communication networks, massive MIMO and mmWave technologies have been shown to be hugely attractive for improving the performance of both WPT and WIT. Massive MIMO promises significant performance gains in terms of spectral efficiency, energy efficiency, security and reliability, compared with conventional MIMO [35]. The mmWave communication paradigm, further to guaranteeing very high data rates, allows highly directional RF waves and large antenna arrays at the transmitter; which makes mmWave very attractive, especially that directional beamforming allows focusing the RF signals into narrow beams, thus contributing to reduce signal attenuation.

Though significant advantages are promised by operation in the mmWave frequencies, in the previous part of this thesis it was clearly shown that a major obstacle inherent to these bands is the signal attenuation due to rain.

In this part of the thesis, relay-assisted communication is considered in a system operating in the mmWave band, and where the energy supply relies on harvesting. Contrary to reported works, where the relay harvests energy from the source signal before forwarding it to the destination, here the source node is assumed to be energy constrained and performs harvesting of energy originating from the relay. The relay implements massive MIMO and the system operates under rain attenuation.

That is, in addition to his ability to receive signals from the source then forward them to the destination, the relay can also send RF signals to the source, for energy harvesting purpose. The basic idea of a wireless communication system in which a node can act as either a relay or a BS, although this is the first time it is considered in the context of wireless energy harvesting and information transmission; is not new, and goes back to 2002, when Dousse et al. introduced the concept of hybrid networks [63], in which an ensemble of BS connected by a wired network is placed within an ad hoc network, and can also act as relays [63, 64]. That is, the source nodes, e.g. a UE, can rely on the hybrid relay to harvest energy and power its communications.

2.4.2 Major Contributions

In comparison to existing works, the contributions of this part can be summarized as follows:

- Firstly, a comprehensive channel model which accurately models the signal propagation in the system under study, is developed. The rainfall effect, the path loss, and both the LOS and the NLOS components of the small-scale fading, are all accounted for. Analytical properties on the obtained channels' vectors are derived, which are not only important but also lay foundation for the subsequent performance analysis.

- Energy harvesting at the source node is investigated. The asymptotic behaviours (in the sense of large number of relay antennas, M) of both the energy that is harvested at the source during the WPT time, and the power that is available at the source node (P_s) during the data transmission time, are derived. The results disclose that both P_s and E_s increase linearly with M. This scaling law indicates that in massive MIMO settings, significant energy gains can be achieved at the harvesting node, especially in the absence of rain. In light weather, the relay can significantly decrease its transmit power, as per the regulations on the transmit power for safety reasons.

- The signal transmission from the source to the destination, and the corresponding system performance, are analyzed. Specifically: (a) The expression of the received signal at the destination is expanded so as to easily express the system SNR. The end-to-end SNR is derived. (b) The asymptotic behaviours of both the spectral efficiency (C) and the system throughput (T_R) are analyzed w.r.t. large M. From this, novel expressions are derived, and yield new insights into the system performance. In particular, i) the system metrics are shown to be deterministic, and can then be determined in advance since the different system and channel parameters involved therein are known. Further, ii) in light-rain and non-severe path loss environments, C and T_R are expected to increase logarithmically w.r.t. M. Given the high values of M in massive MIMO settings, significant performance gain is expected. Moreover, iii) C and T_R are shown to decrease exponentially w.r.t. the raining parameters (absorption coefficient and optical depth), which increase w.r.t. the operating frequency. Given that the said parameters can be very high, in practice rain attenuation can hinder the energy and data transmission no matter M. (c) Pertinent case studies are investigated. These include heavy rain and path-loss conditions, moderate/light rain and not-too-severe path loss, and long harvesting time.

- Finally, the optimal harvesting fraction time that maximizes throughput is investigated, in light/moderate weather and path loss, through numerical evaluation.

This work [65], which detailed contents are appended in Appendix F, was published in Proceedings, IEEE Global Communications Conference, 2017.

Chapter 3

Concluding Remarks

The purpose of this thesis was the modeling and understanding of potential performances of the next-generation of wireless communication networks, with information transmission and energy transfer/harvesting, under regular- and massive MIMO. The ultimate goal being to model, analyze and understand the performances of system with simultaneous wireless information and energy transfer, the work through the final target was divided into four main steps.

In the initial step, for getting familiar with information transmission in regular- and massive MIMO systems, a new and comprehensive channel model was first developed, and a generalized analysis for the spectral efficiency of both regular- and massive MIMO systems was conducted. The channel model considered major natural environmental and antenna physical parameters, including path loss, shadowing, multi-path fading, antenna correlation, antenna polarization, environmental cross-polarization coupling, and antenna cross polarization discrimination. Analytical performance evaluation was then conducted, and revealed explicitly the effect of various parameters on the spectral efficiency. In particular, it was attested that the spectral efficiency increases faster with respect to the fading severity parameter, than to the shadowing severity parameter, and the spectral efficiency of massive MIMO is determined by the correlation characteristics at the end with fewer antennas, instead of the end with more antennas, in case the Weichselberger method-based correlation model is applied. Also, massive MIMO deployments where the number of transmit antennas is higher than the number of the receive antennas has little effect on the spectral efficiency when the said numbers increase with a fixed ratio.

After deeply understanding the information transmission in both the regular- and massive MIMO systems, and, importantly, mastering their modeling and performance analysis frameworks, in the second step of the thesis the purpose was to deeply understand the information transmission in massive MIMO systems, under both the centralized configuration (referred to as C-MIMO) and the distributed configuration (referred to as D-MIMO), as well as the technical tools for their modeling and performance analysis. In this regards, the thesis considered a novel comprehensive analytical channel model where major natural environmental and antenna physical parameters were accounted for, including path loss, shadowing, multi-path fading and antenna correlation. The analysis and the related results revealed that the C-MIMO scheme does not always underperform D-MIMO, although the latter exhibits a higher multiplexing gain. Further, the uplink performance of massive MIMO was shown to be mainly determined by the antenna correlation at the user equipment side, given that the Weichselberger correlation model is applied. For practical purposes, it was demonstrated that for the D-MIMO scheme with circular topology of radius r_{c} and circular antenna array of radius r_{a}, the optimal value of r_{a} that maximizes the average spectral efficiency is accurately established by $r_{\mathrm{a}}^{\mathrm{opt}} = r_{\mathrm{c}}/1.31$.

With the above mentioned steps completed, in the third stage of the thesis, and prior to addressing the simultaneous energy harvesting and information transmission topic, the thesis first focused on the wireless power transfer (WPT)/wireless energy harvesting (WEH), i.e. on a system model where only power transfer/energy harvesting is considered. In this regards, the performance of WPT in millimeter wave (mmWave) massive MIMO systems was studied, based on a comprehensive channel model which accounts for the effects of rainfall, path loss and small-scale fading, and applies to both rainy and non-rainy operating conditions. Results attested that the harvested energy at each user equipment increases linearly with the number of access point antennas, but regardless of the number of antennas, rain attenuation can significantly affect the WPT and/or make it impossible in a wide range of scenarios. This particular results shows that further measurements and investigations are then required for a feasible implementation of WPT in the mmWave band, in rainy regions. For practical purposes, we demonstrated that for a WPT system coverage of outer radius R_{n} and exclusion radius R_{e}, the average energy can significantly increase with decreasing R_{e} and R_{n}, confirming the small-cells configurations (e.g. microcells and picocells) to be a suitable platform for WPT in mmWave massive MIMO networks.

Finally, the thesis analyzed the performance of systems with simultaneous wireless information and power transmissions. The network considered was a relay-aided system, operating in millimeter wave (mmWave) bands, with massive MIMO, where the source needs to harvest energy sent by the relay for powering its data transmission to the destination. A comprehensive MIMO channel model, accounting for rainfall effects, path loss and small-scale fading, was developed. This model describes the signal propagation on all system links, while applying to both rainy and non-rainy operating environments. It was confirmed that the harvested energy and the transmit power at the source exhibit a linear increase w.r.t. the number of relay antennas, M. Also, the asymptotic spectral efficiency and the throughput were shown to logarithmically increase w.r.t. M in good weather. However, in many cases, the energy and information transmission processes can be highly hindered and/or stopped due to rain attenuation regardless of M, which shows how necessary it is to conduct more measurements and investigations to ensure a viable implementation of these processes in mmWave massive MIMO systems. The optimal value of the energy harvesting time that maximizes the system throughput was also investigated, providing important information on the optimal setting to perform in the system in order to achieve the best performances.

In all the works conducted in this thesis, novel comprehensive channel models were developed and extensive performance analysis was conducted, providing important frameworks and key metrics. The results obtained brought very important insights that are applicable to next generation of wireless communication networks, and useful for researchers, designers and manufacturers.

Appendices

Appendix A

Channel Modeling and Capacity Analysis of Large MIMO in Real Propagation Environments[2]

Cet article a dû être retiré de la version électronique en raison de restrictions liées au droit d'auteur.
Vous pouvez le consulter à l'adresse suivante :
DOI : 10.1109/ICC.2015.7248527

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[2] The following is the content of [6], which was summarized in Chapter 2.1.

Appendix B

Spectral-Efficiency Analysis of Regular- and Large-Scale (Massive) MIMO with a Comprehensive Channel Model[3]

Cet article a dû être retiré de la version électronique en raison de restrictions liées au droit d'auteur.
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DOI : 10.1109/TVT.2016.2620489

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[3] The following is the content of [7], which was summarized in Chapter 2.1.

Appendix C

Spectral-Efficiency Analysis of Massive MIMO Systems in Centralized and Distributed Schemes[7]

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DOI : 10.1109/TCOMM.2016.2519513

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[7] The following is the content of [35], which was summarized in Chapter 2.2.

Appendix D

Scaling Laws for Wireless Energy Transmission in mmWave Massive MIMO Systems[12]

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DOI : 10.1109/ICC.2017.7997319

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[12] The following is the content of [57], which was summarized in Chapter 2.3.

Appendix E

Wireless Power Transfer in mmWave Massive MIMO Systems with/without Rain Attenuation[16]

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[16] The following is the content of [58], which was summarized in Chapter 2.3.

Appendix F

Energy and Information Transmission in Relay-Aided mmWave Massive MIMO Systems[21]

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[21] The following is the content of [65], which was summarized in Chapter 2.4.

Appendix G

Publications Lists

G.1 Publications Included in the Thesis

[1] G. N. Kamga, M. Xia, and S. Aïssa, “Channel modeling and capacity analysis of large MIMO in real propagation environments,” in Proc. IEEE ICC’15, London, UK, June 2015, pp. 1447-1452.

[2] G. N. Kamga, M. Xia, and S. Aïssa, “Spectral-efficiency analysis of regular- and large-scale (massive) MIMO with a comprehensive channel model,” IEEE Trans. Veh. Technol., vol. 66, no. 6, pp. 4984-4996, June 2017.

[3] G. N. Kamga, M. Xia, and S. Aïssa, “Spectral-efficiency analysis of massive MIMO systems in centralized and distributed schemes,” IEEE Trans. Commun., vol. 64, no. 5, pp. 1930-1941, May 2016.

[4] G. N. Kamga and S. Aïssa, “Scaling laws for wireless energy transmission in mmWave massive MIMO systems,” in Proc. IEEE ICC’17, Paris, France, May 2017, pp. 1-6.

[5] G. N. Kamga and S. Aïssa, “Wireless power transfer in mmWave massive MIMO systems with/without rain attenuation,” IEEE Trans. Commun., To Appear.

[6] G. N. Kamga and S. Aïssa, “Relay-aided energy and information transmission in

mmWave Massive MIMO systems," in Proc. IEEE GLOBECOM'17, Singapore, Dec. 2017, pp. 1-6.

G.1.1 Publications Not Included in the Thesis

1. G. N. Kamga, M. Xia, and S. Aïssa, "Unified MIMO channel model for mobile satellite systems with ancillary terrestrial component", in Proc. IEEE ICC'14, Sydney, Australia, June 2014, pp. 2449-2453.

2. G. N. Kamga, M. Xia, and S. Aïssa, "A unified performance evaluation of integrated mobile satellite systems with ancillary terrestrial component," in Proc. IEEE ICC'15, June 2015, London, UK, pp. 1447-1452.

3. G. N. Kamga and K. B. Fredj and S. Aïssa, "Multihop cognitive relaying over composite Multipath/Shadowing Channels," IEEE Trans. on Veh. Technol., vol. 64, no. 8, pp. 3807-3812, Aug. 2015.

4. G. N. Kamga, Mirette Sadek, and Sonia Aïssa, "Adaptive handoff for multi-antenna mobile satellite systems with ancillary terrestrial component", in Proc. IEEE ICC'16, Kuala Lumpur, Malaysia, May 2016, pp 1-6.

5. G. N. Kamga and S. Aïssa, "Relay Selection Based Hybrid RF/FSO Transmission over Double-Generalized Gamma Channels under Outdated CSI and Pointing Errors," in Proc. IEEE ICC'18, Kansas City, USA, May 2018.

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Thesis Summary in French

Université du Québec
Institut national de la recherche scientifique
Énergie, Matériaux et Télécommunications

Modélisation et Analyse de la Transmission sans fil de l'Information et de l'Énergie dans les Systèmes MIMO

Résumé

Soumis pour la satisfaction partielle des exigences pour le diplome de Docteur en Philosophie

Par
Gervais Nono Kamga

Membres du Jury

Examinateur Externe	Prof. Jean-François Frigon, École polytechnique de Montréal
Examinateur Externe	Prof. Wessam Ajib, Université du Québec à Montréal
Examinateur Interne	Prof. Douglas O'Shaughnessy
Directeur de Recherche	Prof. Sonia Aïssa INRS–Énergie, Matériaux et Télécommunications

Abstract

La future génération des systèmes de communications sans fil est attendue comme une révolution dans le domaine des télécommunications. Ces futurs systèmes offrent une immense capacité de réseau, des débits de données énormes, pour un nombre très élevé d'utilisateurs et des connexions simultanées avec de grands déploiements de capteurs, ainsi que des gains très élevés. Ces gains sont, entre autres, en termes d'efficacité spectrale, d'efficacité énergétique et de latence. Pour permettre l'émergence de tels réseaux, il est nécessaire de satisfaire les besoins fondamentaux de l'approvisionnement énergétique, et la disponibilité/l'utilisation efficace du spectre de fréquences.

Les techniques de transfert d'énergie sans fil (TES) sont solides, fiables et ont le potentiel de remplacer la recharge filaire (avec fils), actuellement utilisée mais exigente. Ceci en mettant à disposition des utilisateurs, des sources d'énergie presque illimitées. En raison des avantages exceptionnels promis par ces techniques, le monde universitaire et l'industrie étudient activement des solutions pour permettre aux futurs réseaux d'implémenter les techniques de TES, où les noeuds du réseau pourront, simulanément, collecter/transmettre de l'énergie, tout en traitant des signaux de données. D'autre part, la technique de transmission multi-antennes, connue sous le nom de *multiple-input multiple-output (MIMO)* conventionnel, depuis la dernière décennie et, plus récemment, le MIMO massif (appelé *massive MIMO*) ; représentent de puissantes technologies sans fil pour améliorer considérablement l'efficacité spectrale, et même l'efficacité énergétique. Évidemment, une amélioration en termes d'efficacité spectrale, représente une solution solide au problème d'utilisation/de disponibilité du spectre de fréquences disponible.

Du fait des capacités ci-dessus des techniques MIMO conventionel et *massive MIMO*, ainsi que des techniques de TES, ces technologies sont devenues des candidats solides pour le développement et l'émergence des réseaux de communications sans fil de la prochaine génération. La compréhension théorique et le déploiement pratique de ces systèmes nécessitent d'évaluer d'abord leurs performances, tout en tenant compte de diverses caractéristiques de propagation du signal et

du réseau. Pour contribuer à cela, cette thèse vise à fournir une structure analytique pour la modélisation de canal et l'analyse de performance des réseaux de communications sans fil de la prochaine génération, où il y a traitement de l'information et/ou collecte d'énergie, avec implémentation des techniques MIMO conventionel et/ou *massive MIMO*. Plus précisément, dans la première partie de la thèse, une analyse généralisée et unifiée de l'efficacité spectrale des systèmes MIMO conventionel et/ou *massive MIMO* est conduite, où les principales caractéristiques de propagation radio et les paramètres du réseau d'antennes sont pris en compte. Ces caractéristiques comprennent les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets, la corrélation aux antennes, la polarisation aux antennes, le couplage à polarisation croisée environnemental (appelé dans la littérature le *cross-polarization coupling (XPC)*) ; et la polarisation croisée de discrimination aux antennes (appelée dans la littérature le *cross-polarization discrimination (XPD)*).

La deuxième étape de la thèse porte sur l'analyse de performance des systèmes *massive MIMO*, en termes d'efficacité spectrale, aussi bien dans la configuration centralisée que dans la configuration distribuée, appelées respectivement MIMO centralisé (*centralized MIMO (C-MIMO)*) et MIMO distribué (appelé *distributed MIMO (D-MIMO)*). Cette analyse se base sur un nouveau modèle de canal, complet, développé dans cette même partie de la thèse, et qui intègre tous les paramètres environnementaux réels et les caractéristiques des antennes, à savoir les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets, et la corrélation aux antennes.

Dans la troisième partie de la thèse, le TES est étudié, en considérant les systèmes de TES implémentant le *massive MIMO*, et opérant dans les bandes millimétriques, où les conditions pluvieuses et non pluvieuses sont considérées, et le modèle de canal prenant en compte les effets de la précipitation, de pertes de trajet et l'évanouissement multi-trajets.

Enfin, la quatrième étape de la thèse étudie la performance des réseaux avec, simultanément, la collecte de l'énergie et la transmission de l'information. Le système considéré implémente le *massive MIMO*, et fonctionne dans les bandes millimétriques, tout en tenant en compte les effets de la précipitation, de pertes de trajet et l'évanouissement multi-trajets.

Tout au long de la thèse, lors de la réalisation du projet, la méthodologie adoptée consiste à modéliser le canal, en considérant les principales caractéristiques de propagation radio et les paramètres du réseau d'antennes ; puis la conduite de l'analyse de performances, en termes d'efficacité spectrale (dans les deux premières parties de la thèse), de l'énergie collectée (dans la troisième partie) et du *throughput* (dans la quatrième partie). Ces indicateurs de performances sont tous calculés et donnés sous forme analytique fermée (c-à-d *closed-form*, en anglais) puis étudiés sous différents scénarios pratiques clés, pour obtenir des informations importantes qui ne sont pas seulement très importantes pour la compréhension des différentes technologies dans les futurs réseaux, mais bénéficieront également aux concepteurs et aux fabricants dans la conception de ces systèmes et les noeuds du réseau.

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Chapitre 1

Résumé du Travail

1.1 Contexte et Motivations

La future génération de réseaux de communications sans fil, e.x. la future cinquième génération (5G), promettent des avantages remarquables, qui seront rentables tant pour les opérateurs économiques/réseaux que pour les utilisateurs finaux. Ces avantages sont par exemple un gain de capacité de réseau au moins 1000 fois plus grandes que les capacités actuelles, des débits de données supérieurs à plusieurs dizaines de Mbits/sec (ou Gb/s) pour un nombre massif d'utilisateurs, tous pris en charge ; une capacité supérieure à des centaines de milliers de connexions simultanées et prises en charge pour assurer des déploiements massifs de capteurs ; une efficacité spectrale et une efficacité énergétique augmentées d'au moins dix fois, une latence réduite de manière significative par rapport à la LTE actuelle ; et une couverture qui sera considérablement améliorée. Ces fonctionnalités aideront à faire face à la demande extrême des utilisateurs dont le nombre augmente de façon exponentielle, améliorant leur accès aux réseaux et la qualité des services qu'ils reçoivent.

Comme toujours dans les communications sans fil, les nouveaux réseaux devront relever deux défis fondamentaux et majeurs, afin de satisfaire les exigences très élevées pour les infrastructures : *i)* l'approvisionnement en énergie qui permet aux différents noeuds du réseau d'alimenter à la fois leurs tâches internes et leurs transmissions de données ; et *ii)* l'utilisation efficace du spectre (limité) de fréquences.

Afin de résoudre le problème de l'approvisionnement en énergie dans les systèmes de communications sans fil ; récemment, les techniques de transfert d'énergie sans fil (TES) ont été (dé)montrées comme représentant une alternative importante à la recharge filaire (avec fils) actuellement utilisée ; et résoudront les problèmes laborieux liés à la capacité limitée des batteries et la difficulté de recharge, rencontrés dans les réseaux cellulaires actuels [1]. En raison de ces problèmes, et en raison des avantages énormes inhérents à l'utilisation des techniques de TES, ces technologies mobilisent un intérêt très important, dand le monde de la recherche, à travers la planète.

Avec les techniques de TES, une tendance relativement nouvelle consiste à combiner la collecte d'énergie et le traitement de l'information aux mêmes noeuds du réseau, où la collecte de l'énergie permet aux terminaux d'utilisateurs d'extraire, sans fil, de l'énergie à partir de leur signal reçu, de l'environnement, ou de sources d'énergie telles que les balises électriques (appelées *power beacons*). Ainsi, les terminaux sans fil peuvent extraire de l'énergie à partir d'une large gamme de sources d'énergie presque toujours disponibles, ce qui n'est pas le cas avec la recharge par fil. Plusieurs applications exploitent déjà l'utilisation simultanée de techniques de TES et du traitement de l'information, c.f. e.x. [2] pour quelques exemples.

D'autre part, pour surmonter le défi lié à la disponibilité du spectre, augmenter l'efficacité spectrale est inévitable. L'efficacité spectrale mesure l'efficacité avec laquelle un spectre de fréquences limité est exploité, et augmenter l'efficacité spectrale entraine l'augmentation du débit de tranmission qui peut être atteint sur une bande passante donnée, dans un système de communications spécifique. Depuis la dernière décennie, la technique de transmission multi-antennes, connue sous le nom de *multiple-input multiple-output (MIMO)* conventionnel, s'est imposée comme une technologie sans fil puissante pour améliorer l'efficacité spectrale (et donc avoir des débits de communications plus élevés), et même pour avoir une meilleure capacité de tolérance d'erreurs, par rapport aux configurations avec une seule antenne aux noeuds du réseau. Comme un important pas de plus, le MIMO massif (appelé *massive MIMO*), introduit en 2010 [3], où des dizaines ou quelques centaines d'antennes sont déployées à l'une ou l'autre des extrémités d'un lien sans fil, a la capacité d'améliorer considérablement l'efficacité spectrale. En outre, le *massive MIMO* apporte également des gains considérables en termes d'efficacité énergétique, et même de sécurité et de fiabilité par rapport au *MIMO* conventionnel [4]. Et comme cela a été démontré dans plusieurs travaux publiés, en utilisant la technique du *MIMO* conventionnel ou du *massive MIMO*, dans les réseaux combinant le tranfer/l'emmagasinage d'énergie et le traitement/transfert de l'information, les performances de ces systèmes sont considérablement améliorées. Pour ces raisons le *massive*

MIMO est devenu une pierre angulaire dans l'émergence des futurs systèmes 5G [4, 5].

1.2 Objectif Principal du Projet

Pour la compréhension théorique et le déploiement pratique des réseaux de la future génération dans des environnements de propagation réels, où les techniques du *MIMO* conventionnel ou du *massive MIMO* sont considérées, avec ou sans collecte simultanée d'énergie ; une tâche préalable consiste à effectuer la modélisation, ainsi que l'évaluation des performances en fonction de diverses caractéristiques clé de propagation et de paramètres du réseaux ; où l'analyse en forme fermée (dite *closed-form*) est de loin souhaitable, sinon nécessaire. Dans ce souci, l'objectif principal de la présente thèse est de contribuer à la modélisation et l'analyse de performances, des réseaux de communications sans fil de nouvelle génération, avec transmission d'informations et/ou collecte d'énergie, dans des systemes adoptant les technique du *MIMO* conventionnel ou du *massive MIMO*. Pour atteindre cet objectif, le travail se divise en quatre étapes principales, résumées comme suit.

1.3 Modelisation et Analyse pour *MIMO* Conventionnel et *Massive MIMO*

1.3.1 Motivations et Revue de la Littérature

Comme souligné dans l'introduction, pour, entre autres, résoudre les problèmes de pénurie du spectre de fréquences dans la nouvelle génération de réseaux de communications sans fil ; la technique MIMO conventionnel garantit une amélioration significative de l'efficacité spectrale, et le *massive MIMO* promet de bien meilleures performances.

Avant qu'il soit possible de déployer des systèmes MIMO réguliers ou *massive MIMO* dans des systèmes multi-utilisateurs, en pratique, la tâche la plus fondamentale est d'analyser et de comprendre théoriquement les performances de ces réseaux dans une configuration point-à-point.

Une telle analyse et évaluation de la performance exige la prise en compte, non seulement des éléments de l'environnement naturel, mais aussi les paramètres physiques de l'antenne, où ces derniers (c-à-d les paramètres) sont particulièrement important pour le *massive MIMO*. En fait, par rapport aux systèmes MIMO conventionnels, la taille limitée des émetteurs/récepteurs rend la séparation efficace entre les antennes multiples difficilement réalisable et, par conséquent, la technologie de polarisation de l'antenne est largement considérée comme une technique prometteuse dans le déploiement du MIMO à grande échelle en pratique. Cependant, la corrélation entre les antennes avec la même polarisation reste inévitable. Par conséquent, le développement d'un modèle analytique de canal MIMO englobant les paramètres environnementaux naturels de propagation et les dispositifs physiques d'antennes, est la pierre angulaire de la conception et de l'analyse de performance du MIMO à grande échelle en pratique. Néanmoins, une telle modélisation générale qui permet une traçabilité mathématique facile est loin d'être simple, en raison des nombreux paramètres impliqués. Ceci sans oublier la complexité analytique extrêmement élevée pour les valeurs statistiques clés des canaux, comme la probabilité de panne et l'efficacité spectrale.

En général, les paramètres environnementaux comprennent principalement les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets, le couplage à polarisation croisée environnemental (c-à-d le *cross-polarization coupling (XPC)*) ; tandis que les paramètres d'antenne concernent la corrélation aux antennes, la polarisation aux antennes, et la polarisation croisée de discrimination aux antennes (c-à-d le *cross-polarization discrimination (XPD)*).

Dans la littérature scientifique, de nombreuses publications ont été consacrées à l'analyse de l'efficacité spectrale des systèmes MIMO en fonction de différents modèles de canaux, où, cependant, chacun des modèles MIMO existants est consacré à un scénario spécifique. Parmi ces modèles, le plus simple concerne l'évanouissement multi-trajets, comme les modèles de Rayleigh et Rice, où, dans les deux cas, les modèles statistiques des canaux sont conjointement gaussiennes et l'analyse de performance peut être effectuée en utilisant la bien connue théorie de la matrice de Wishart [6]. Le modèle de Nakagami, connu pour décrire plus précisément les environnements de propagation réels, et englobant Rayleigh et Rice comme cas particuliers, a été exploité dans [7] pour analyser l'efficacité spectrale des systèmes MIMO où, en raison de la grande difficulté de la traçabilité mathématique, certaines bornes sur l'efficacité spectrale ont été proposées. Comme un pas de plus, un modèle abordant l'effet conjoint de l'évanouissement multi-trajets, de l'ombrage et des pertes de trajet a été proposé dans [8]. Plus récemment, [9] a considéré l'évanouissement multi-trajet basique de Rayleigh, avec la corrélation, en conjonction avec l'effet d'ombrage et les pertes de trajet, pour étudier les systèmes MIMO distribués. Dans [8] et [9], les performances du système ont été étudiées au moyen de bornes sur l'efficacité spectrale.

Par ailleurs, pour répondre aux défis liés à la corrélation de l'antenne et à la taille limitée des émetteurs/récepteurs où la séparation efficace entre les antennes est difficile à réaliser, la technologie de polarisation de l'antenne a été largement appliquée, ce qui a permis d'obtenir les modèles de canaux MIMO polarisés. Par exemple, la configuration d'antenne à polarisation orthogonale a été montrée comme rentable sur le plan spatiale et pratique [10]. Sur la base de ce modèle, la performance de la transmission MIMO avec la diversité de polarisation a été analysée dans le contexte de l'évanouissement de type Rayleigh et Rice [11–13], et le modèle de propagation de Loo [14].

Pour faciliter la traçabilité mathématique, chacun des travaux de MIMO mentionnés ci-dessus ne tient compte que des scénarios spécifiques, où certains paramètres environnementaux ou physiques d'antennes sont ignorés. Même le modèle de canal spatial MIMO recommandé par le projet de partenariat de troisième génération (3GPP), est présenté au moyen d'un algorithme informatique sans mesure de performance analytique en *closed-form*, empêchant le développement de règles/protocoles de gestion de réseau avancés [15]. Il va sans dire que, une analyse générale applicable aux scénarios les plus populaires avec la prise en compte des principaux paramètres physiques dans le déploiement pratique n'est pas seulement impérative, mais aussi nécessaire pour une évaluation de performance unifiée et en *closed-form* des systèmes MIMO réalistes.

Plus précisément, cette partie du projet se subdivise en deux travaux publiées via [16] et [17], où, en raison de la complexité analytique extrêmement élevée dans l'évaluation de performance en *closed-form* basée sur le modèle complet proposé, l'analyse est effectuée en termes de borne supérieure sur l'efficacité spectrale.

Au mieux de ma connaissance, aucun travail préalable dans la littérature scientifique n'a examiné de manière exhaustive lesdits paramètres de propagation et d'antenne tous ensemble, pour effectuer une analyse de performance unifiée et en *closed-form* de systèmes MIMO conventionnels ou *massive MIMO*, tel que détaillé dans mes articles publiés [16] et [17].

1.3.2 Résumé des Contributions

Dans cette partie initiale du projet, un nouveau modèle de canal, complet et unifié, est d'abord proposé et une analyse généralisée pour l'efficacité spectrale des systèmes *MIMO* conventionnel et *massive MIMO*, est menée. Les principales caractéristiques liées à la propagation radio et les paramètres des antennes sont pris en compte, y compris les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets, la corrélation aux antennes, la polarisation aux antennes, le XPC et le XPD. Dans un premier article publié [16], le modèle MIMO général et unifié proposé est basé sur le très populaire modèle de Kronecker, où les paramètres environnementaux principaux et les paramètres physiques de l'antenne susmentionnés sont pris en compte ; et l'analyse est consacrée au *MIMO* conventionnel. Étant donné que le modèle de Kronecker ne permet pas une analyse en *closed-form* de l'efficacité spectrale et présente certaines limites quant à sa précision ; un deuxième article a été publié [17], et exploite la méthode de Weichselberger pour reformuler le modèle de Kronecker, en donnant un nouveau modèle de canal qui, bien qu'il soit plus complexe, *i)* permet une analyse de performance en *closed-form* et de plus ; *ii)* présente les avantages liés à la précision du modèle basé sur la méthode de Weichselberger. Dans ce deuxième article, l'analyse de l'efficacité spectrale prend en compte les deux types de *MIMO* conventionnel et *massive MIMO.*

Grâce à leur grande généralité, les modèles de canaux et les analyses développées dans [16] et [17] pour cette partie de la thèse, qui sont corroborés par les résultats de simulation de type Monte-Carlo, aident les concepteurs de systèmes dans la conception et l'évaluation de performances des systèmes de MIMO conventionnel ou *massive MIMO*, tout en tenant compte des phénomènes réalistes caractérisant à la fois l'environnement de propagation et les réseaux d'antennes dans les réseaux.

Plus de détails (e.x. outils et méthodologie mathématiques) concernant l'analyse de l'efficacité spectrale et les résultats obtenus se trouvent dans [16, Sections III, IV] et [16, Annexe A] (pour les les systèmes *massive MIMO*) et [17, Sections III–V] et [17, Appendices A–C] (pour MIMO conventionnel et *massive MIMO*). Les travaux [16] et [17], ont été publiés respectivement dans les *Proceedings*, via la International Conference on Communications (ICC) en 2015, et dans le journal *IEEE Transactions on Vehicular Technology.*

1.4 Modélisation et Analyse des Systèmes *Massive MIMO* dans les Schémas Centralisés et Distribués

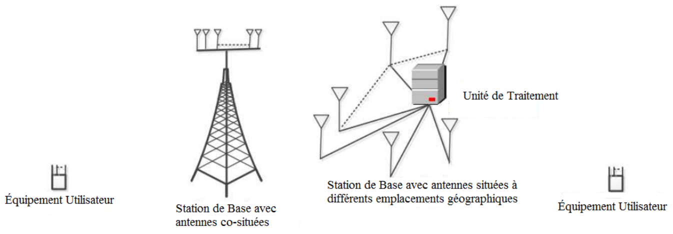
1.4.1 Motivations et Revue de la Littérature

En rappelant le rôle très important du *massive MIMO* dans la prochaine génération de réseaux sans fil, et en suivant les deux travaux ci-dessus réalisés dans la première étape de la thèse, où l'on considère le MIMO conventionnel et le *massive MIMO* ; cette partie du projet vise à développer un modèle de canal et à fournir un cadre pour l'évaluation unifiée des performances des systèmes *massive MIMO*, où le modèle de canal développé est général et tient en compte les principaux paramètres environnementaux, et les paramètres physiques de l'antenne.

Pour implémenter le *massive MIMO* dans les réseaux sans fil, deux schémas différents peuvent être adoptés (voir, par exemple, [18–20]) : *i)* MIMO centralisé (appelé *centralized MIMO (C-MIMO)*), où les antennes sont situées au même emplacement dans les deux cotés transmetteur et récepteur comme illustré dans la Fig. 1.1-a (qui est essentiellement équivalent au système MIMO conventionnel) ; et *i)* MIMO distribué (appelé *distributed MIMO (D-MIMO)*), où les antennes à la station de base sont déployées à des emplacements géographiques différents tout en étant connectées à travers des liens à très haut débit tels que les câbles à fibre optique, comme le montre la Fig. 1.1-b.

D'un point de vue pratique, le C-MIMO est plus facile à analyser mathématiquement et à déployer physiquement, comparé au D-MIMO. En fait, contrairement au premier, ce dernier souffre de différents degrés de pertes de trajet causés par différentes distances d'accès aux différentes antennes distribuées, ce qui rend l'analyse et l'évaluation de la performance plus difficiles. En outre, comme l'emplacement des antennes dans la configuration D-MIMO a un effet significatif sur les performances du système, l'optimisation de ces emplacements d'antennes est cruciale [19, 21]. Cette tâche peut devenir très difficile en raison des nombres importants (massifs) d'antennes du transmetter/récepteur. D'autre part, en pratique, l'emplacement arbitraire des antennes ou la topologie optimale peuvent entraîner un coût prohibitif pour l'infrasctrure réseau, ainsi que le coût d'installation pour la configuration distribuée.

La technique du D-MIMO présente cependant plusieurs avantages par rapport à C-MIMO, comme une puissance d'émission inférieure, un gain de multiplexage plus élevé, une efficacité spectrale plus élevée, une zone de couverture améliorée et une facilité de planification du réseau



(a) MIMO Centralisé (b) MIMO Distribué

Figure 1.1 – Deux configurations de systèmes MIMO point-à-point : (a) C-MIMO, où les antennes sont situées au même emplacement aussi bien du côté station de base que du côté terminal utilisateur et, par conséquent, les distances entre le terminal utilisateur et les antennes de la station de base sont presque identiques ; (b) D-MIMO, où les antennes de la station de base sont déployées à des emplacements géographiques différents tout en étant reliées l'une à l'autre au travers d'une unité de traitement, ce qui implique que les distances entre le terminal utilisateur et les antennes de la station de base sont différentes.

[22,23]. Ceci dit, les deux schémas, C-MIMO et D-MIMO, représentent des choix prometteurs pour la mise en oeuvre pratique de la technique *massive MIMO*, chacun selon les critères potentiellement préférables mentionnés ci-dessus.

Quelle que soit la configuration, centralisée ou distribuée, pour prendre en compte les caractéristiques de propagation et pour comprendre les performances et le comportement du système dans des environnements physiques réels, deux tâches fondamentales sont : *i)* développer un modèle de canal analytique, où les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets et la corrélation aux antennes sont pris en compte ; et *ii)* effectuer une évaluation analytique des performances et évaluer les facteurs clés qui déterminent la performance du système.

En particulier, pour les systèmes D-MIMO, différentes pertes à travers différents chemins, liés aux différentes antennes de la station de base, sont essentielles à la réalisation de la diversité transmetteur/ récepteur. En outre, la corrélation à l'antenne est inhérente à la réalisation du *massive MIMO*, en raison du manque d'espace physique suffisant pour séparer le grand nombre d'antennes au cas où elles seraient placées au même emplacement.

En pratique, la performance du MIMO point-à-point sert de base pour une évaluation de performance dans les configurations multi-utilisateurs. En outre, l'application du *massive MIMO* point-à-point trouve de nombreuses applications, par exemple les liaisons sans fil haute vitesse entre stations de base [24]. Cependant, en dépit de l'extrême importance du *massive MIMO* en point-à-point, il n'existe aucun travail qui considère avec succès tous les paramètres susmentionnés (pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets et la corrélation aux antennes) tout en développant un modèle de canal et en effectuant une analyse de performance en *closed-form*. En particulier, il a été montré dans [25] que pour les canaux MIMO, l'efficacité spectrale augmente linéairement avec le minimum entre les nombres d'antennes au transmetteur et au récepteur, même si ces nombres tendent vers l'infini. Le résultat asymptotique lorsque le nombre d'antennes d'un seul côté passe à l'infini a été donné dans [26,27]. Dans [25–27], seul l'évanouissement multi-trajets a été considéré, alors que les pertes de trajet, l'effet d'ombrage et la corrélation à l'antenne ont été ignorés. Dans [28–30], la capacité des canaux multi-antennes avec corrélation a été étudiée, dans les deux régimes de nombres finis d'antennes (dans [28]) et de nombre infini d'antennes (dans [28–30]), où seul l'évanouissement de type Rayleigh et la corrélation à l'antenne, étaient considérés. Comme présenté ci-dessus, dans mes travaux [16] et [17], un modèle de canal complet, prenant en compte les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets, la corrélation aux antennes, la polarisation aux antennes, le XPC et le XPD ; a d'abord été développé. Ensuite, une borne supérieure sur l'efficacité spectrale du système point-à-point en C-MIMO a été calculée en utilisant l'inégalité d'Hadamard sur le déterminant, et analysée de manière asymptotique dans le sens d'un très grand nombre d'antennes au transmetteur/récepteur.

1.4.2 Différences Clés avec les 2 Travaux Précédents

Entre mes travaux précédents [16] et [17] et le travail mené dans cette partie de la thèse, deux différences majeures sont les suivantes :

a) Modèle du système : Seule la configuration C-MIMO est considéré dans [16] et [17] alors que C-MIMO et D-MIMO sont étudiés conjointement dans le travail mené dans cette partie de la thèse. En particulier, la contribution majeure de ce dernier travail est pertinente pour D-MIMO.

b) Méthodologie d'analyse : Dans [16] et [17], une borne supérieure sur l'efficacité spectrale est analysée dans le sens de grand nombre d'antennes au transmeteur/récepteur, en utilisant l'inégalité d'Hadamard sur le déterminant. Cependant, dans le travail mené dans cette partie du projet, l'efficacité spectrale est exacte, et est d'abord calculée puis analysée au sens d'un grand nombre d'antennes au récepteur, en utilisant la théorie des vecteurs aléatoires très longs.

1.4.3 Résumé des Contributions

Comme souligné plus haut, cette deuxième étape de la thèse vise à modéliser et analyser les performances des systèmes *massive MIMO*, à la fois dans les configurations centralisées et distribuées. En tenant compte des paramètres environnementaux réels et des caractéristiques physiques des antennes, à savoir les pertes de trajet, l'effet d'ombrage, l'évanouissement multi-trajets, et la corrélation aux antennes ; un nouveau modèle de canal, complet, est d'abord proposé sous forme analytique en *closed-form*. Ce modèle est applicable aux deux types de schémas MIMO, soit le C-MIMO et le D-MIMO. Ensuite, sur la base du modèle proposé, une analyse exacte est effectuée, où le comportement asymptotique de l'efficacité spectrale du canal MIMO, sous les configurations centralisées et distribuées, est calculé et comparé. Par la suite, une étude de cas est effectuée en appliquant les résultats obtenus aux réseaux MIMO avec couverture circulaire, où les résultats ultérieurs apportent de nouvelles informations éclairantes et pertinentes sur la conception et le déploiement de systèmes *massive D-MIMO*, en pratique. En particulier, il est démontré que pour un systeème D-MIMO avec topologie circulaire de rayon de cellule r_c avec un réseau d'antenne circulaire de rayon r_a, la valeur optimale de r_a qui maximise l'efficacité spectrale moyenne est donnée par $r_\mathrm{a}^\mathrm{opt} = r_\mathrm{c}/1.31$.

Le modèle de canal complet proposé, l'analyse développée et les résultats obtenus, grâce à leur généralité et leur compacité, peuvent servir de référence pratique pour concevoir et analyser les performances des systèmes *massive D-MIMO* dans des environnements de propagation physique réels.

Plus de détails sur la modélisation des canaux, l'analyse de l'efficacité spectrale et les résultats obtenus se trouvent dans [31, Sections II–V] et [31, Appendices A–E]. Ce travail [31], a été publié dans le journal *IEEE Transactions on Communications.*

1.5 Modélisation et Analyse pour le Transfert de Puissance Sans Sil, dans les Systèmes Massive MIMO Opérant dans les Bandes Millimétriques

1.5.1 Motivations et Revue de la Littérature

Comme indiqué plus haut, assurer la transmission d'énergie et la transmission de l'information, les deux en simultané, est devenu une tendance très importante pour les systèmes de communications sans fil, compte tenu des avantages y afférant. Cette approche occupera une place importante dans les réseaux sans fil de la prochaine génération. Avant d'aborder la transmission d'énergie et la transmission de l'information en simultané, cette thèse se concentre d'abord, dans sa troisième étape, sur le transfert/collecte d'énergie, c'est-à-dire sur un modèle de système où seul le transfert de puissance/collecte d'énergie est considéré. Puis, ensuite, la thèse se penche sur le traitement de l'information et le transfert de puissance/emmagasinage d'énergie, en simultané.

Classiquement, les dispositifs sans fil, dans, par exemple, les systèmes cellulaires et les réseaux de capteurs, sont alimentés par des batteries qui, une fois qu'elles sont épuisées ou à des niveaux critiques, doivent être rechargées ou remplacées manuellement. La recharge filaire (par fil), qui est actuellement la principale façon de fournir l'énergie aux batteries de périphériques sans fil, est une routine obligatoire mais très difficile et exigente, et peut même être un problème majeur dans de nombreux cas. Par exemple, si la batterie de l'appareil ne peut pas être rechargée lorsque cela est nécessaire, une interruption brusque du service produira non seulement une mauvaise expérience utilisateur, mais aussi des pertes dramatiques, par e.x. des données critiques dans les applications sensibles ou même des situations d'urgence. Même lorsque des batteries de rechange sont disponibles, le remplacement fréquent de la batterie est une tâche ardue et incommode (e.x. dans les larges réseaux de capteurs), coûteuse, parfois dangereuse (e.x. dans les zones interdites/dangereuses) ou même impossible (e.x. les dispositifs médicaux implantés) [32].

Comme alternative, les techniques de TES sont très prometteuses. Depuis récemment, elles attirent un intérêt significatif du monde de la R&D en raison de leur capacité à fournir une alimentation en énergie illimitée aux appareils sans fil, grâce à la collecte d'énergie à partir de sources plus accessibles, et en permanence. Les technologies de TES actuelles peuvent être classées en deux catégories, selon les mécanismes physiques qu'ils emploient, à savoir le couplage par résonance magnétique et les rayonnements électromagnétiques.[1] Ce travail se place dans la dernière catégorie, c'est-à-dire qu'il prend en compte le TES dans le domaine radio-frequence (RF), où les propriétés radiatives des champs lointains des ondes électromagnétiques sont exploitées de sorte qu'un récepteur de puissance puisse accumuler de l'énergie à distance à partir des signaux RF rayonnés par un émetteur [32, 33]. Le TES basé sur les signaux RF présente de nombreux avantages pratiques par rapport au couplage par résonance magnétique, comme une plage de fonctionnement plus longue, un coût de production plus faible et un facteur de forme au récepteur plus petit [32].

L'idée de la résonance magnétique et/ou des techniques de transfert de puissance à champ lointain dans le domaine RF n'est pas nouvelle, mais date plutôt de la fin des années 1800. Heinrich Hertz, en 1887 [34, Fig. 24], a conçu le premier prototype de TES basé sur la résonance magnétique. Une tentative de transmission sans fil de la puissance à Colorado Springs, CO, aux États-Unis, a été menée en pratique par Nikola Tesla, en 1899. Cependant, aucune donnée n'a été recueillie au cours de cette expérience, sur si une quantité significative de puissance serait disponible à n'importe quel point éloigné. Le premier transfert de puissance qui a été exécuté avec succès a été fait par Harrell V. Noble au Laboratoire Westinghouse, où il fut montré au public, à la Foire mondiale de Chicago de 1933 à 1934 [35]. Ensuite, Lav R. Varshney, en 2008, au MIT, a proposé pour la première fois de transporter de la puissance et les données, simultanément, dans les systèmes de communications sans fil [36].

Actuellement, dans la pratique, le TES trouve de nombreuses applications. Par exemple, il est très utile pour les réseaux de capteurs avec contrainte sur leur énergie, qui est utilisé dans, par exemple, le transport intelligent, la surveillance structurelle et la détection d'intrusion [37]. De plus, le TES peut être utilisé pour charger des appareils à faible puissance tels que les indicateurs de température et d'humidité, et les écrans à cristaux liquides [38]. Il est possible d'utiliser le TES dans les applications de calculs basique, de détection et de communications [39].

Bien que les techniques de TES promettent d'énormes avantages, des problèmes importants doivent être résolus avant qu'elles ne puissent être implémentées dans la prochaine génération de réseaux de communications sans fil. Tout d'abord, à cause de la grande atténuation de l'énergie des

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[1] En rappelant que dans le couplage inductif, la distance entre le transmetteur et le récepteur ne peut pas dépasser quelques centimètres, cette technologie de recharge sans fil n'est donc pas adaptée pour faire face aux problèmes laborieux liés à la capacité limitée des batteries (qui doivent être régulièrement rechargées) et la difficulté de recharge, rencontrés dans les réseaux cellulaires actuels [1].

ondes électromagnétiques en fonction de la distance, seule une fraction de l'énergie rayonnée par un transmetteur d'énergie, peut être collectée par le récepteur, ce qui limite sévèrement la portée et les possibilités du TES [1, 40]. Deuxièmement, contrairement au transfert de l'information où la sensibilité des récepteurs est d'environ -60 dBm, dans le TES, la sensibilité d'un récepteur typique d'énergie est de -10 dBm [32]. Troisièmement, un autre problème grave avec le TES est le rendement du transfert/collecte d'énergie, qui est d'autant plus important que la sensibilité des récepteurs d'énergie actuelle n'est pas bonne.

Pour faire face à ces problèmes et réaliser le TES en pratique, deux solutions principales consistent à *i)* concentrer l'énergie RF en faisceaux étroits, appelé *beamforming d'énergie* [41] ; et *ii)* du point de vue de la conception du réseau, rendre la distance entre les transmetteurs et les récepteurs d'énergie, aussi petite que possible. Plus récemment, le *massive MIMO* s'est montré très attrayant pour améliorer les performances du TES, avec d'énormes avantages en perspective. En fait, une étude récente sur la "faisabilité du TES utilisant des systèmes *massive MIMO*" a révélé plusieurs gains importants [2].

D'autre part, l'approche réseau qui consiste à exploiter les bandes millimétriques, et qui est un candidat principal pour les futurs réseaux 5G, offre toutes les trois solutions clés décrites ci-dessus pour augmenter les performances du TES, c'est-à-dire *i)* une transmission hautement directionnelle avec les ondes RF ; *ii)* des distances plus courtes entre les points d'accès et les terminaux utilisateurs ; et *iii)* un grand nombre d'antennes aux points d'accès. En effet, les recherches récentes avancent que les systèmes opérant dans les bandes millimétriques fonctionnent généralement avec la formation de faisceaux directionnels au transmetteur/récepteur en utilisant des réseaux à très grands nombres d'antennes et un déploiement dense de points d'accès, pour une couverture comparable à celle rencontrée dans les bandes ultra hautes fréquences (UHF) [42]. De toute évidence, ces caractéristiques de conception dans les bandes millimétriques sont attrayantes pour le TES à champ lointain et peuvent considérablement augmenter les performances des systèmes de TES.

Cependant, la propagation du signal dans les fréquences millimétriques est soumise à de sévères déficiences, ce qui pourrait affecter de manière significative le transfert d'énergie. Tout d'abord, les signaux dans les bandes millimétriques sont sensibles au blocage, car ils souffrent d'un faible pouvoir de pénétration (à travers divers obstacles) et la diffraction [43, 44]. Un autre obstacle majeur aux signaux millimétriques est leur grande sensibilité aux conditions météorologiques, en particulier à l'atténuation due à la pluie. Des pluies sévères telles que de fortes pluies, les grandes averses (e.x.

dans les États-Unis) et les moussons (e.x., dans le sud de la Chine) peuvent même interrompre les communications dans les bandes millimétriques [45]. Dans les systèmes cellulaires UHF actuels, sous 6 GHz, l'effet de la pluie est généralement considéré comme une atténuation de propagation uniforme pendant la planification du réseau [43, 44]. Cette approche est exacte dans ces systèmes où le diamètre typique d'une goutte de pluie est beaucoup plus petit que la longueur d'onde du signal [46]. Dans les systèmes opérant dans les bandes millimétriques, une approche complètement différente est nécessaire. En fait, puisque les longueurs d'onde des signaux millimétriques sont comparables à la taille des gouttes de pluie, ces signaux subissent une absorption et une diffusion sévères lorsqu'ils sont transmis à travers la pluie et souffrent, par conséquent, d'une atténuation sévère de l'amplitude et d'une fluctuation de phase [47].

Au vue des discussions menées ci-dessus, plusieurs questions nécessitent des réponses concernant les gains potentiels du TES à travers les fréquences millimétriques : (1) Qu'est-ce que, en termes d'amélioration de l'énergie collectée par un terminal utilisateur, le gain potentiel en utilisant la technique du *massive MIMO* dans les bandes millimétriues, lorsqu'il n'y a pas de pluie ? Plus précisément, quelles sont les lois qui découlent de l'utilisation de grands nombres d'antennes dans le TES à travers les bandes millimétriques, lorsque les conditions de fonctionnement sont non pluvieuses ? (2) En cas de pluie, quelles pertes le processus de TES rencontrerait, et comment l'énergie collectée diminue-t-elle avec le taux de pluie ? (3) Lorsque les paramètres de la pluie augmentent d'un certain facteur, ce qui signifie une pluie plus forte, quel est le nombre d'antennes et/ou le niveau de puissance d'émission (dans la liaison descendante) nécessaire pour retrouver la valeur initiale de l'énergie collectable avant la dégradation des conditions de pluie ? (4) Lorsque le récepteur d'énergie est mobile, et que sa distance au transmetteur d'énergie varie de façon aléatoire, quelle est l'énergie moyenne que ce récepteur peut collecter au fil du temps, et quels sont les impacts du nombre d'antennes et de la pluie sur l'énergie collectée ? (5) Pour la conception du réseau, quels paramètres peuvent être modifiés et comment le faire afin de compenser (ou diminuer) l'effet de la pluie, ou tout simplement augmenter la performance du TES lorsqu'il n'y a pas de pluie ?

Cette partie de la thèse répond à ces questions via une étude approfondie, et fournit un cadre analytique pour caractériser les performances du TES dans les futurs réseaux opérant dans les bandes millimétriques avec ou sans atténuation dûe à la pluie.

Comme mentionné ci-dessus, des gains importants provenant de l'utilisation du *massive MIMO* dans les systèmes de TES ont récemment été mis en évidence dans [2]. L'accent était mis sur le calcul de la probabilité de panne du système, dans les UHF. Dans ce travail, la configuration *massive MIMO* n'a été considérée que dans les simulations. Ceci dit, l'analyse en *closed-form* de l'énergie collectée avec le *massive MIMO* les lois subséquentes dans les bandes UHF ou millimétriques n'ont pas été faites dans [2]. Plus récemment, [48] et [44] ont étudié le TES dans les bandes millimétriques, et ont conclu que la collecte d'énergie dans ces bandes fournit un gain substantiel par rapport à ce qu'on obtient dans les fréquences inférieures. Contrairement au présent travail où les lois mathématiques et analytiques sur l'énergie en fonction du nombre d'antennes sont données, les auteurs dans [48] et [44] se concentrent sur la recherche de la probabilité de couverture d'énergie ; pour les cas où un dispositif extrait soit l'énergie uniquement, soit l'énergie et l'information, à partir des signaux millimétriques ; en utilisant des outils de la géométrie stochastique. De plus, et au mieux de ma connaissance, aucun des articles existants dans la littérature n'a encore analysé l'effet de la pluie dans l'évaluation de la performance des réseaux de TES, comme cela a été réalisé dans cette partie de la thèse.

Pour atteindre le but de cette partie du projet, où les questions susmentionnées sont toutes répondues, le travail se conduit à travers deux articles : le premier [49], publié comme conférence, via les *Proceedings*, International Conference on Communications (ICC) en 2017 ; et le second [50], qui généralise le travail dans [49], en troisième ronde de revue, dans le journal *IEEE Transactions on Communications*.

1.5.2 Résumé des Contributions

En comparaison aux travaux existants, cette partie de la thèse étudie la performance du TES dans les systèmes *massive MIMO*, opérant dans des bandes millimétriques, où les conditions pluvieuses et non pluvieuses sont considérées. En tenant compte des effets de précipitation, de pertes de trajet et l'évanouissement multi-trajets, un modèle de canal MIMO complet a d'abord été développé, et convient à la modélisation de la propagation d'énergie dans les systèmes de TES opérant dans les bandes millimétriques et implémentant le *massive MIMO*. Ensuite, en exploitant la loi de la conservation de l'énergie ainsi que la théorie des vecteurs aléatoires très longs, l'énergie transférée par l'émetteur d'énergie (un point d'accès hybride (PAH)) et collectée par les terminaux d'utilisateurs est analysée et étudiée sous plusieurs scénarios importants. Ceci révèle plusieurs résultats et informations clés sur la performance et la conception du système considéré, résultats qui seront très importants non seulement pour la compréhension du TES dans les réseaux de la future génération, mais dont bénéficieront également les concepteurs et fabricants, dans leur travail de conception de ces systèmes et de leurs noeuds d'exploitation.

Comme mentionné ci-dessus, ce travail a été divisé en deux parties, la première, déjà acceptée comme article de conférence dans les *Proceedings*, International Conference on Communications (ICC) en 2017 ; et le second [50], qui fait l'objet d'une toisième ronde de revue dans le journal *IEEE Transactions on Communications.*

1.6 Modélisation et Analyse du Transfert de Puissance et de Transmission d'Information en Simultanée, dans les Systèmes *Massive MIMO* Opérant dans les Bandes Millimétriques

1.6.1 Motivations et Revue de la Littérature

Comme le chapitre précédent de cette thèse, et dans sa continuité, cette partie du projet étudie également la performance des réseaux sans fil avec TES, dans les systèmes *massive MIMO* opérant dans les bandes millimétriques, mais où la transmission de l'information et le transfert/la collecte d'énergie sont effectués simultanément. On considère un système de transmission à double sauts, où la communication entre un noeud source (S) et un noeud de destination (D) est assistée par un noeud relais, placé entre S et D, où le protocole *amplifie-puis-transmet* (appelé *amplify-and-forward (AF) protocol*) est implémenté.

En fait, un autre problème majeur dans les communications sans fil est l'atténuation sévère du signal en fonction de la distance, en raison des pertes de trajet et/ou des obstacles sur le chemin entre l'émetteur et le récepteur. Pour répondre à cette préoccupation, les techniques de relayage, où un ou plusieurs relais placés entre l'émetteur et son récepteur final assurent la communication, a été largement adopté dans les réseaux de communications RF. Pour profiter des avantages importants obtenus grâce à l'utilisation de relais dans les systèmes de communications sans fil, les chercheurs ont récemment adopté le concept de relayage dans les réseaux où le traitement de l'information et le TES ont lieu simultanément (voir, e.x. [51–54]. Dans ces travaux [51–54], le relais doit extraire l'énergie du signal reçu du noeud source afin de transmettre ce signal au noeud de destination.

D'autre part, et comme l'ont souligné les parties précédentess de cette thèse, dans le contexte de la prochaine génération de réseaux de communications sans fil, les technologies *massive MIMO* et l'exploitation des bandes millimétriques sont extrêmement attrayantes pour améliorer la performance du TES et du transfert des informations. La technique du *massive MIMO* promet des gains de performance significatifs en termes d'efficacité spectrale, d'efficacité énergétique, de sécurité et de fiabilité, par rapport au MIMO conventionnel [31]. Le paradigme de communications dans les bandes millimétriques, afin de garantir des débits de données très élevés, permet de générer des ondes RF hautement directionnelles et est compatible avec l'implémentation de très larges nombres d'antennes à l'émetteur. Ceci rend les bandes de fréquences millimétriques très attrayantes. En particulier, la formation de faisceaux hautement directionnels permet de focaliser les signaux RF en faisceaux étroits, contribuant ainsi à réduire l'atténuation du signal.

Bien que des avantages importants soient promis par l'opération dans les fréquences millimétriques, dans la partie précédente de cette thèse, il a été clairement démontré qu'un obstacle majeur inhérent à ces bandes est l'atténuation du signal due à la pluie.

Dans cette partie de la thèse, la communication assistée par relais est considérée, dans un système fonctionnant dans la bande millimétrique, et où l'approvisionnement en énergie repose sur le TES. Contrairement aux travaux déjà publiés dans la littérature, où le relais extrait de l'énergie à partir du signal source avant de l'acheminer vers la destination, le noeud source a une contrainte en énergie et effectue la collecte d'énergie provenant du relais. Le relais implémente le *massive MIMO* et le système est soumis à l'atténuation dûe à la pluie.

Ceci dit, en plus de sa capacité à recevoir des signaux provenant de la source puis de les transférer vers la destination, le relais peut également envoyer des signaux RF à la source, à des fins d'extraction d'énergie. L'idée de base d'un système de communications sans fil dans lequel un noeud peut agir soit comme un relais soit comme une station de base, bien que ce soit la première fois que cette idée est considérée dans le contexte du TES et de la transmission de l'information ; n'est pas nouvelle. L'idée remonte à 2002, lorsque Dousse *et al.* ont introduit le concept de réseaux hybrides [55], dans lequel un ensemble de stations de base connectées par un réseau filaire, est placé dans un réseau *ad hoc*, et peut aussi servir de relais [55, 56]. Ceci dit, le noeud source (qui peut être, par exemple, un terminal utilisateur), peut s'appuyer sur le relai hybride pour accumuler de l'énergie et ainsi alimenter ses communications.

1.6.2 Résumé des Contributions

Comme dit plus haut, dans sa quatrième étape, cette thèse effectue la modélisation et l'analyse de la performance des réseaux avec, simultanément, la collecte de l'énergie et la transmission de l'information. On considère un système de transmission avec *massive MIMO*, opérant dans les bandes millimétriques, où un relais assiste la communication longue-distance entre un noeud source et un noeud destination, le relais étant placé entre les deux noeuds. Le noeud source doit d'abord collecter de l'énergie, pour pouvoir transmettre ses données au relais. Un modèle complet de canal MIMO est d'abord développé, où les effets de la pluie, de pertes de trajet et de l'évanouissement multi-trajets sont considérés, ce qui modélise correctement la propagation du signal sur tous les liens du système. Les expressions asymptotiques de l'énergie et de la puissance à la source sont ensuite calculées, et contribuent à évaluer l'efficacité et le *throughput*, en expressions asymptotiques, pour différents scénarios importants. En outre, la valeur optimale du temps de collecte d'énergie qui maximise le *throughput* est étudiée. Les résultats obtenus montrent que, par temps clair (c'est à dire quand il n'y a pas de pluie), les expressions asymptotiques de l'efficacité spectrale et du *throughput* augmentent logarithmiquement avec le nombre d'antennes au relais, et que les deux mesures diminuent de façon exponentielle avec les paramètres de pluie.

Le travail accompli dans cette partie, a été accepté pour publication, via la conférence *IEEE Global Communications Conference*, 2017.

Chapitre 2

Listes des Publications

2.1 Publications Incluses dans la Thèse (par Ordre d'Inclusion)

1. G. N. Kamga, M. Xia, and S. Aïssa, "Channel modeling and capacity analysis of large MIMO in real propagation environments," in *Proc. IEEE ICC'15*, London, UK, June 2015, pp. 1447-1452.
2. G. N. Kamga, M. Xia, and S. Aïssa, "Spectral-efficiency analysis of regular- and large-scale (massive) MIMO with a comprehensive channel model," *IEEE Trans. Veh. Technol.*, vol. 66, no. 6, pp. 4984-4996, June 2017.
3. G. N. Kamga, M. Xia, and S. Aïssa, "Spectral-efficiency analysis of massive MIMO systems in centralized and distributed schemes," *IEEE Trans. Commun.*, vol. 64, no. 5, pp. 1930-1941, May 2016.
4. G. N. Kamga and S. Aïssa, "Scaling laws for wireless energy transmission in mmWave massive MIMO systems," in *Proc. IEEE ICC'17*, Paris, France, May 2017, pp. 1-6.
5. G. N. Kamga and S. Aïssa, "Wireless power transfer in mmWave massive MIMO systems with/without rain attenuation," *IEEE Trans. Commun.*, under third round of review.
6. G. N. Kamga and S. Aïssa, "Relay-aided energy and information transmission in mmWave Massive MIMO systems," in *Proc. IEEE GLOBECOM'17*, Singapore, Dec. 2017, Accepted.

2.2 Publications Non Incluse dans la Thèse

1. G. N. Kamga, M. Xia, and S. Aïssa, “Unified MIMO channel model for mobile satellite systems with ancillary terrestrial component”, in *Proc. IEEE ICC'14*, Sydney, Australia, June 2014, pp. 2449-2453.
2. G. N. Kamga, M. Xia, and S. Aïssa, “A unified performance evaluation of integrated mobile satellite systems with ancillary terrestrial component,” in *Proc. IEEE ICC'15*, June 2015, London, UK, pp. 1447-1452.
3. G. N. Kamga and K. B. Fredj and S. Aïssa, “Multihop cognitive relaying over composite Multipath/Shadowing Channels,” *IEEE Trans. on Veh. Technol.*, vol. 64, no. 8, pp. 3807-3812, Aug. 2015.
4. G. N. Kamga, Mirette Sadek, and Sonia Aïssa, “Adaptive handoff for multi-antenna mobile satellite systems with ancillary terrestrial component”, in *Proc. IEEE ICC'16*, May 2016, Kuala Lumpur, Malaysia, pp 1-6.
5. G. N. Kamga and S. Aïssa, “Mixed RF/FSO systems with partial relay selection and outdated channel state estimation over Double Generalized Gamma channels with Generalized pointing errors,” *IEEE Trans. Wireless Commun.*, submitted for possible publication.
6. G. N. Kamga and S. Aïssa, “On the Outage of Energy Harvesting based Opportunistic Cooperative Communications,” *IEEE Wireless Commun. Lett.*, submitted for possible publication.

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