THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Characterization of Small Antennas & Wireless Devices for MIMO Systems in Rich Isotropic Multipath & Random Line-of-Sight

by

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To my family & friends

Abstract

The current thesis is about over-the-air (OTA) performance characterization of wireless terminals in rich isotropic multipath (RIMP) environment as well as in pure line-of-sight (LOS) environment while not ignoring the random positions and orientations of the mobile terminals due to randomness of the user. The latest mobile wireless terminals such as iPhone and iPad can be used in any random position and orientation thereby making the received LOS-component to appear as a random voltage at the antenna ports. The terms such as "RIMP" and "Random-LOS" are coined to represent two limiting environments for OTA performance characterization of mobile terminals. The RIMP environment is emulated by reverberation chambers while pure-LOS is emulated by anechoic chambers. Mobile terminals are mostly used in multipath environments, e.g. indoor environments and therefore the focus of this thesis is about measuring and simulating diversity gains, channel capacity, and throughput of wireless devices in a RIMP environment. The papers [A-D] discuss some work related to using RIMP as a reference environment and study convergence of diversity gains and capacity.

The reverberation chamber has been used to measure both passive antennas and complete active wireless devices for many years. Recently, the active measurements of Long Term Evolution (LTE) or 4G devices have become very important in order to test implemented Multiple-Input Multiple-Output (MIMO) diversity and Orthogonal Frequency Division Multiplexing (OFDM) technology. Features such as adaptable modulation scheme, system bandwidth, coding rate, and diversity have made communication system more robust and adaptable to the environment. A theory to estimate the OTA throughput of LTE devices including the diversity gains due to MIMO and OFDM is presented and tested for different LTE system bandwidths and coherence bandwidths in papers [E-H].

During the last few years, we have developed multipath environment simulation tools to study convergence, to validate measurements in RIMP, and to study other multipath environments for comparison. Most of the work in this thesis is based on these simulation tools i.e. Rayleigh-lab and ViRM-lab. A section of many listed papers discuss about these simulation tools.

At Chalmers University, a multiport ultra-wideband (UWB) bow-tie antenna has been designed and developed during last few years. The OTA performance characterization of this antenna has been done by measurements and simulations in RIMP environment. The results are discussed in papers [I-J].

The OTA performance characterization of single-port mobile terminals has been studied for several years now. Today, we have LTE mobile terminals with multiport antennas which must be be characterized for OTA environments. The OTA performance characterization of a two-port mobile phone mockup on both sides of the head following standardized talk positions is presented and discussed in papers [K-L].

The OTA performance of a compact UWB antenna developed for mobile phone applications at Linkoping University is discussed in paper M. The antenna covers all important bands such as GSM, UMTS, LTE, Bluetooth, and WLAN, etc.

Keywords: OTA, RIMP, Rayleigh, reverberation chamber, random LOS, LTE, MIMO.

Preface

This report is a thesis for the degree of Licentiate of Engineering at Chalmers University of Technology. This work has been carried out between October 2009 and March 2013 at the Antenna Group, Department of Signals and Systems, Chalmers University of Technology. Professor Per-Simon Kildal has been the main supervisor as well as the examiner and Professor Jan Carlsson has been the co-supervisor.

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I would like to especially acknowledge my supervisor Prof. Per-Simon Kildal for giving me an exciting opportunity to study for a PhD degree and work at Chalmers University of Technology. I am very thankful to you for creating jolly and positive atmosphere through your sense of humor, emotions, energy and passion which you dedicate to your work. Your innovative ideas, commercialization, encouragement and appreciation helped me to work restlessly on different interesting projects. I'm proud to be a part of your group.

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I would also like to appreciate the antenna family for organizing activities and developing a very homely atmosphere in the corridor. Thank you all: Chen, Nima, Ashraf, Elena, Hasan, Astrid, Eric, Oleg, Aidin, Carlo, Rob, Esperanza, Prof. Jian, Prof. Marianna, Prof. Eva, Prof. Kishk, and all former members of the group. I would like to thank all my colleagues and friends at S2 for great cooperation and joyful environment. I am also thankful to Helene and Jingya; it was fun to learn Swedish with you. I would also like to acknowledge the administrative and the management staff at the university and especially at the department for their support and quick response.

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I would also like to thank all managers and active contributors involved in CHASE projects and especially SP, Bluetest, Sony, and Ericsson for their contributions, feedback and suggestions. I would like to thank Swedish Governmental Agency for Innovation Systems (VINNOVA) for creating research opportunities by financial support to the scientific and technological development in the society. I am greatly thankful to Chalmers University for providing the best teaching and learning environment with all resources at the institution. I am also thankful to the students in the antenna engineering course to nominate me for Chalmers Pedagogic Award in 2010, which I received.

I want to acknowledge my family and especially my life's first teacher – my mom – for all the efforts she put on me to become what I am today. I want to acknowledge all of my teachers and supervisors for giving me exciting opportunities to work and learn from them.

Last, but not the least, I am extremely thankful to Almighty God for everything I have in life!

Ahmed Hussain

Gothenburg, March 2013.

List of Papers

A. P. Kildal, A. Hussain, U. Carlberg, J. Carlsson, "On using isotropic multipath as reference environment for OTA performance: Uncertainty due to convergence of statistical expectation when estimating ergodic capacity and diversity gain," presented at the European Cooperation in the field of Scientific and Technical Research - COST2100, Alborg, 2010.

B. U. Carlberg, J. Carlsson, A. Hussain, P. Kildal, "Ray based multipath simulation tool for studying convergence and estimating ergodic capacity and diversity gain for antennas with given far-field functions," in 2010 20th International Conference on Applied Electromagnetics and Communications (ICECom), 20-23 Sept. 2010.

C. A. Hussain, P. Kildal, U. Carlberg, J. Carlsson, "About Random LOS in Rician Fading Channels for MIMO OTA Tests," presented at the 2011 International Symposium on Antennas and Propagation (ISAP 2011) Jeju, 2011.

D. A. Hussain, P. Kildal, J. Carlsson, "Convergence of MIMO Capacity & Diversity Gain Due to Randomness of Rician K-factor," will be re-submitted to Special International Journals of Antenna & Propagation, 2013.

E. P. Kildal, A. Hussain, X. Chen, C. Orlenius, A. Skårbratt, J. Åsberg, T. Svensson, T. Eriksson, "Threshold Receiver Model for Throughput of Wireless Devices With MIMO and Frequency Diversity Measured in Reverberation Chamber," Antennas and Wireless Propagation Letters, IEEE, vol. 10, pp. 1201-1204, 2011.

F. A. Hussain, P. Kildal, G. Durisi, "Modeling System Throughput of Single and Multi-port Wireless LTE Devices," in IEEE Antennas and Propagation Society International Symposium, 8-14 July 2012, 2012.

G. A. Hussain and P. Kildal, "Study of OTA Throughput of LTE Terminals for Different System Bandwidths and Coherence Bandwidths," presented at the 7th European Conference on Antennas and Propagation (EUCAP), 2013, Gothenburg, 2013.

H. P. Kildal, A. Hussain, G. Durisi, C. Orlenius, A. Skårbratt, "LTE MIMO multiplexing performance measured in reverberation chamber and accurate simple theory," in Antennas and Propagation (EUCAP), 2012 6th European Conference on, 2012, pp. 2299-2302.

I. A. Hussain, P. Kildal, A. Al-Rawi, J. Yang, "Efficiency, Correlation, and Diversity Gain of UWB Multiport Self-Grounded Bow-Tie Antenna in Rich Isotropic Multipath Environment," presented at the International Workshop on Antenna Technology, 2013. IWAT '13., Karlsruhe, 2013.

J. Al-Rawi, A. Hussain, J. Yang, M. Franzen, C. Orlenius, "A New Compact Wideband MIMO Antenna – The Double-sided Tapered Self-grounded Monopole Array," will be submitted to IEEE Transactions on Antenna & Propagation, 2013.

K. A. Hussain, P. Kildal, U. Carlberg, J. Carlsson, "Diversity Gains of Multiport Mobile Terminals in Multipath for Talk Positions on Both Sides of the Head," presented at the 7th European Conference on Antennas and Propagation (EUCAP), 2013, Gothenburg, 2013.

L. A. Hussain, P. Kildal, "Correlation Between Far-field Patterns on Both Sides of the Head of Two-port Antenna on Mobile Terminal," presented at the Antennas and Propagation Society International Symposium (APSURSI), 2013 IEEE, 2013.

M. A. M. Asghar, M. Malick, M. Karlsson, A. Hussain, "A Multi-wideband Planar Monopole Antenna for 4G Devices", in Microwave and Optical Technology Letters, IEEE, vol. 5, No. 3, pp. 589-593, March 2013.

Other publications:

- H. Raza, J. Yang, A. Hussain, "Measurement of Radiation Efficiency of Multiport Antennas With Feeding Network Corrections," in IEEE Antennas and Wireless Propagation Letters, 2012.
- J. Carlsson, U. Carlberg, A. Hussain, P. Kildal, "About Measurements in Reverberation Chamber and Isotropic Reference Environment," in 2010 20th International Conference on Applied Electromagnetics and Communications (ICECom), 20-23 Sept. 2010.
- A. Hussain, P. Kildal, J. Carlsson, "Uncertainties in estimating ergodic MIMO capacity and diversity gain of multiport antenna systems with different port weights," in Antennas and Propagation (EUCAP), Proceedings of the 5th European Conference on, 2011, pp. 310-314.
- A. Hussain, U. Carlberg, J. Carlsson, P. Kildal, "Analysis of statistical uncertainties involved in estimating ergodic MIMO capacity and diversity gain in Rayleigh fading environment," in ICECom, 2010 Conference Proceedings, 2010, pp. 1-4.
- U. Carlberg, P. Kildal, A. Hussain, J. Carlsson, "On using isotropic multipath as reference environment for OTA performance: ray-based multipath simulation tool for studying convergence and uniqueness of different user-related statistical expectations when estimating ergodic capacity and diversity gain," presented at the European Cooperation in the field of Scientific and Technical Research - COST2100, Alborg, 2010.

Basic reference from Prof. Per-Simon Kildal, which is a part of fundament of my contributions:

- P. Kildal, C. Orlenius, J. Carlsson, "OTA Testing in Multipath of Antennas and Wireless Devices With MIMO and OFDM," Proceedings of the IEEE, vol. 100, pp. 2145-2157, 2012.

Contents

Part I: Introductory Chapters

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Part I

Introductory Chapters

CHAPTER 1 Introduction

Traditionally, antennas had been widely used for line-of-sight (LOS) communication in different civilian and military applications like radios, TV transmissions, satellite communications, microwave links, radars, etc. A lot of studies and research were carried out especially to develop methods to measure the performance of these LOS antennas. The anechoic chamber was developed as a tool to measure LOS antennas and devices. As shown in Fig. 1.1, it has absorbing material on all surfaces (i.e. walls, floor, and ceiling) to emulate the free-space or ideal LOS environment. Many years later, handheld devices such as mobile phones which are most often present in non-line-of-sight (NLOS) or multipath environment became popular. Different methods were developed to measure performance of antennas used in these devices. Today, there is a variety of measurement tools for characterizing over-the-air (OTA) performance of wireless mobile terminals in multipath environments. The reverberation chamber is our favorite tool for OTA measurements due to small size, efficiency, price, and better accuracy. As shown in Fig. 1.2, it is a metallic cavity which produces rich isotropic multipath (RIMP) environment [1, 2]. The comparison of anechoic and reverberation chambers can be studied from [3-6]. The performance of Multiple-input Multiple-output (MIMO) systems and multiport mobile terminals can be measured inside reverberation chamber which follows theoretical results showing the same improvement in the performance by using antenna diversity [7-9].

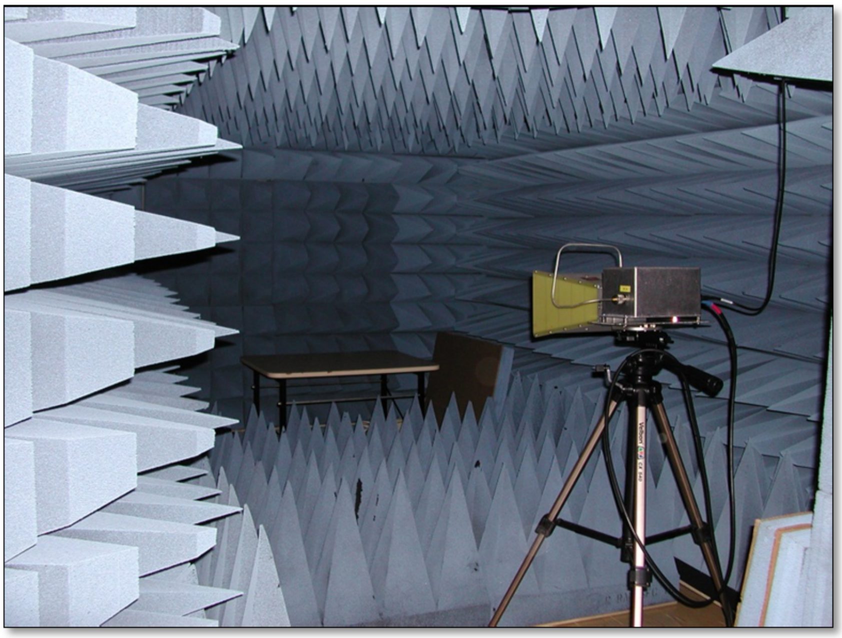

Figure 1.1. A photo of interior view of an anechoic chamber with absorbing material on all sides.

Figure 1.2. A photo showing a metallic cavity which is used as reverberation chamber for OTA measurements of active and passive devices.

Today, we measure OTA performance of both passive (e.g. antennas) and active devices (e.g. mobile terminals) inside reverberation chamber. This helps us to compare different antenna performance (e.g. radiation efficiency) [10-13] as well as complete system performance (e.g. MIMO LTE throughput) [14-19]. A photo of OTA MIMO measurements of LTE device inside reverberation chamber is shown in Fig. 1.3.

Figure 1.3. A photo showing LTE USB modem connected to two external antennas inside reverberation chamber during OTA MIMO LTE throughput measurements.

The measurement accuracy of reverberation chamber studied in [20-27] show that it is very good and the standard deviation is within ±0.5 dB. The environment inside the reverberation chamber is controlled in terms of coherence bandwidth [28-30] and Doppler spread [31, 32]. The measurements performed inside reverberation chamber are repeatable. Some recent examples of passive and active measurements inside reverberation chamber are [19, 33, 34].

A photo of a practical mobile phone mockup together with the head and the hand phantom is shown in Fig. 1.4 which is taken from examples in CST MWS. The measurements and simulations of a multiport mobile phone mockup in RIMP have shown quite good agreement with each other in [34]. The simulations are based on simulated far-field patterns to calculate the diversity gains for different standard talk positions on both sides of the head as defined in [35].

While fixed antenna systems are being measured in anechoic chamber which is emulating free-space environment; and mobile terminals are being measured in reverberation chamber which is emulating multipath environment; there still exist possibilities when mobile terminal users experience a pure-LOS environment or observe LOS component in a multipath environment. The randomness due to user is often forgotten. We argue that LOS experienced by a mobile terminal will become completely random due to its random position and orientation with respect to the base station [1, 36]. We use the terminology "random LOS" to express pure-LOS which becomes 3D-random due to the user. We study OTA performance of device with random position and orientation in the two extreme environments i.e. random LOS and RIMP. Our hypothesis is: "if the performance of device is good in both extreme environments, then its performance will be good in real-life environments as well".

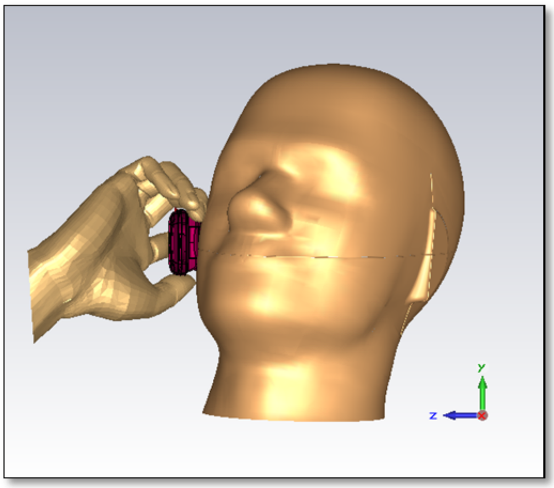

Figure 1.4. A photo showing a practical mobile handset model together with head and hand phantom taken from examples in CST Microwave Studio.

Recent developments at our research group have led to UWB self-grounded bow-tie antenna [33, 37]. This UWB MIMO antenna has been used to study its performance characterization in RIMP and in random LOS. This antenna which is shown in Fig. 1.5 was originally developed at Chalmers University of Technology in Sweden. It is used as a multiport base station antenna for reverberation chambers by Bluetest AB. The performance characterization of this antenna is discussed more in Chapter 6.

We needed to design simulation tools to perform studies based on simulations such as studying convergence of radiation efficiency, diversity gain, etc.; studying random LOS; studying RIMP; studying MIMO performance, etc. At Chalmers University, we have developed numerical tools to simulate OTA performance of terminals e.g. Rayleigh-lab [38] based on random number generator and ViRM-lab [39] which is a ray-based simulation tool. These tools will be discussed more in detail in Chapter 4.

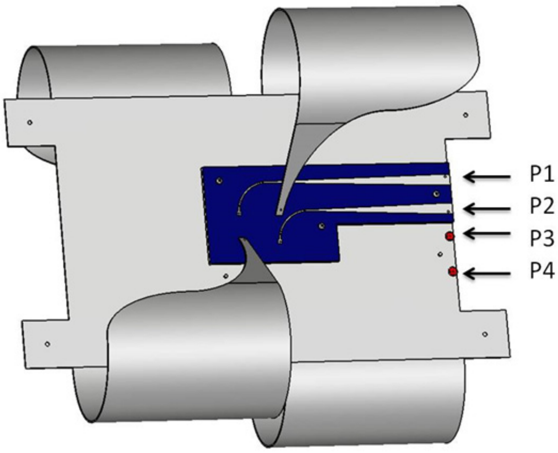

Figure 1.5. A photo showing CST model of four-port UWB self-grounded bow-tie antenna.

The LTE measurements inside reverberation chamber published in our articles are based on a commercially available LTE device. It is important to measure performance of real devices which are commercially available to get a good comparison of good and bad devices. On the other hand, it is difficult to get full control over the device and to get detailed information about it. To avoid this situation and get more control over hardware and software, we are currently trying out Universal Software Radio Peripheral (USRP) designed and developed by Ettus Research and its parent company, National Instruments. As shown in Fig. 1.6, we can see USRPs during conducted measurements. At the moment, no results related to USRPs are presented in this thesis.

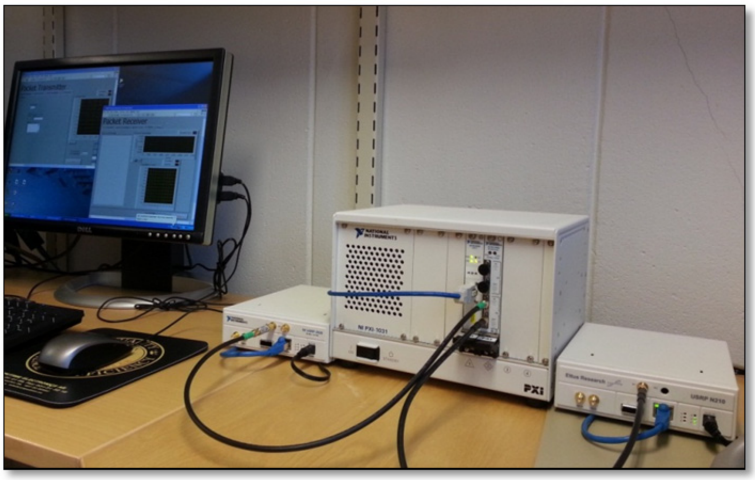

Figure 1.6. A photo showing two USRPs connected via digital attenuator during SISO conducted measurements. Both USRPs and the attenuator are controlled via LabView codes on computer.

CHAPTER 2 Multipath Environment

A multipath environment is simply an environment in which the signal from one antenna takes multiple paths to arrive to another antenna. The signal experiences different phenomena such as reflection, refraction, diffraction, interference, and scattering in the environment due to multipath propagation. The signals in a multipath environment interfere constructively and destructively. The peaks in the received fading signal appear due to constructive interferences and deep nulls appear due to destructive interferences. Due to different propagation effects, the received signal amplitude, phase, polarization, etc. become random. Mobile terminals e.g. handsets, phones, etc. undergo strong fading in multipath environments such as urban and indoor environments. The instantaneous fading of the signal is completely random for different frequency, space, time and polarization. Different techniques such as diversity in frequency, space, time, or polarization can be used to overcome deep fading nulls and improve the performance of the mobile terminals in multipath environments. A multipath environment is usually characterized by the distribution of the fading signal e.g. Rayleigh fading, Rician fading, etc.; delay spread or coherence bandwidth; coherence time or Doppler spread; number of scatterers; position and distribution of scatterers; polarization imbalance.

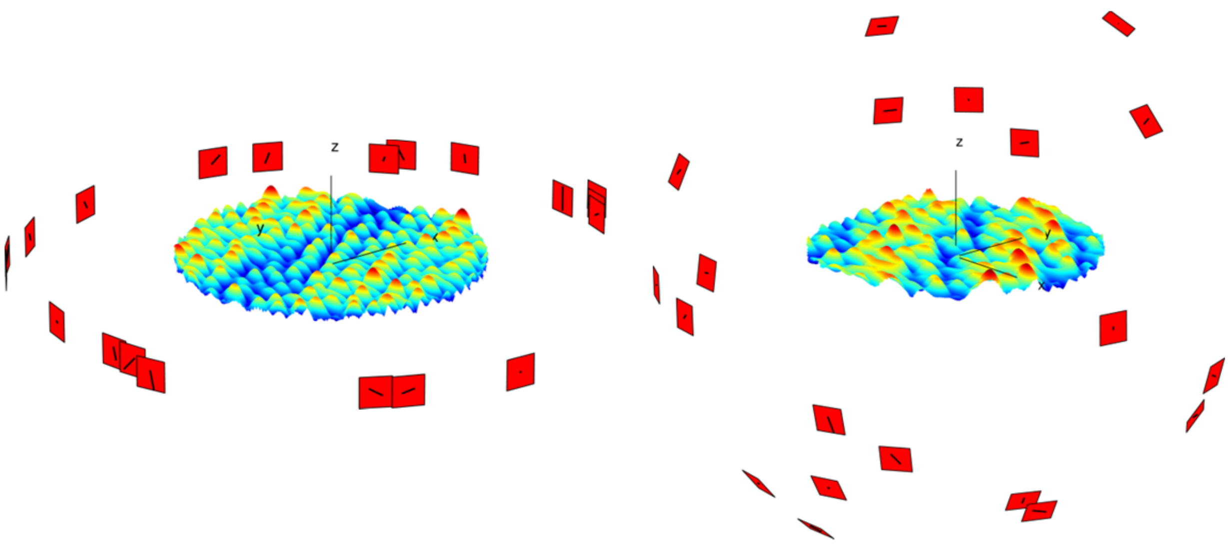

Figure 2.1. Illustration showing incoming waves with random angle-of-arrival, polarization angle, amplitude and phase in 2D (left) and 3D (right) multipath environments.

Several groups such as 3GPP, CTIA, COST, etc. have proposed different models for propagation in multipath environments. Often it becomes a point of discussion if the multipath environment model should be 2D or 3D, as shown in Fig. 2.1. It is argued in some studies that in real-life multipath environments the waves are mostly in the horizontal plane forming a 2D multipath environment. We use multipath simulation tool e.g. ViRM-lab and show that simulations or measurements performed in a 2D multipath environment will depend on the position and orientation of the mobile terminal [2, 39]. Different positions and orientations in a 2D multipath environment will give different results. On the other hand, in a 3D multipath environment the results are always unique and do not depend on the position or orientation of the terminal. A comparison of simulated apparent diversity gain (ADG) performance of dipoles in 2D and 3D multipath environment is presented in [2], also shown in Fig. 2.2.

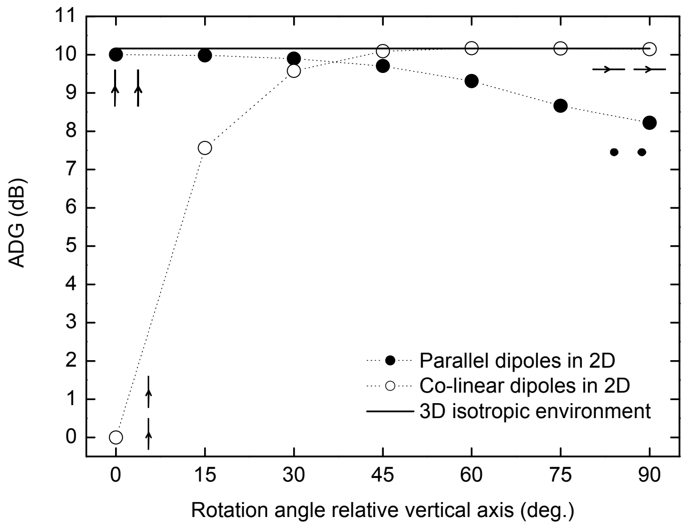

Figure 2.2. Apparent diversity gains of parallel and co-linear dipoles in 2D and 3D multipath environments.

The reverberation chamber is a metallic cavity and has stirrers to stir the energy by mechanical movement of the plates inside the chamber as shown in Fig. 2.3. The device-under-test (DUT), e.g. laptop, lies on the platform stirrer which rotates the DUT inside the multipath environment. The long metal sheet between the transmit antenna and DUT is to block LOS-component for better accuracy in the measurement results. The reverberation chamber emulates rich isotropic multipath (RIMP) environment [1] which is a 3D environment with many enough incoming waves towards the receiving antenna as illustrated in Fig. 2.1 (right). The angle-of-arrival (AoA), phase, and polarization angle of these incoming waves are uniformly distributed. The received complex voltages at the antenna ports are complex Gaussian distributed. The reverberation chamber has been used for measuring active and passive devices inside multipath environment for more than 10 years now. The antenna efficiency and diversity gain are examples of passive measurements and the total radiation power, total isotropic sensitivity, and throughput are examples of active measurements inside reverberation chamber.

The measurement and simulation results of any antenna or device inside a RIMP environment are unique as well as independent of its position and orientation in the environment. The cumulative distribution function (CDF) of the received voltages at the antenna port always follows Rayleigh distribution inside RIMP environment for directive antennas as well as for small antennas. This means that the measurements inside RIMP environment are independent of the shape of the far-field radiation patterns. The result of this can be seen from comparison of diversity gain performance and Shannon's channel capacity of incremental electric dipoles and pencil beams in RIMP or 3D environment as shown in Fig 2.4. The pencil beams with -3 dB half beamwidth equal to 45 degrees are used. From results it is quite clear that unlike in a 2D environment, the diversity gains and channel capacities converge to a unique value in a 3D environment independent of the position and orientation of the device as well as independent of the shape of the far-field patterns.

In real-life environments, a multipath environment may have a LOS component as well. This will change the distribution of the fading in the environment from Rayleigh to Rician. The Rician K-factor is the ratio of powers of LOS component and NLOS components. Mathematically,

$$K = \frac{P_{LOS}}{P_{NLOS}} \tag{2.1}$$

Traditionally, Rician fading environment is considered a multipath environment with fixed LOS-component. This is true if we consider only one user with fixed position and orientation. In real-life, the users have arbitrary positions and orientations of the mobile terminal. The received power due to LOS-component is random due to random position and orientation of the mobile terminal.

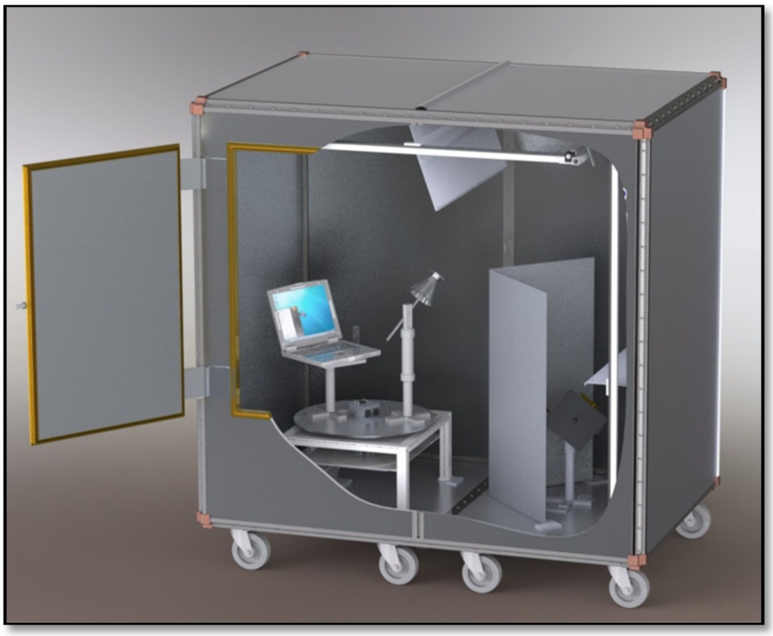

Figure 2.3. A drawing of an interior view of reverberation chamber (one wall is partly removed) with plate stirrers and a rotating platform stirrer carrying the device-under-test.

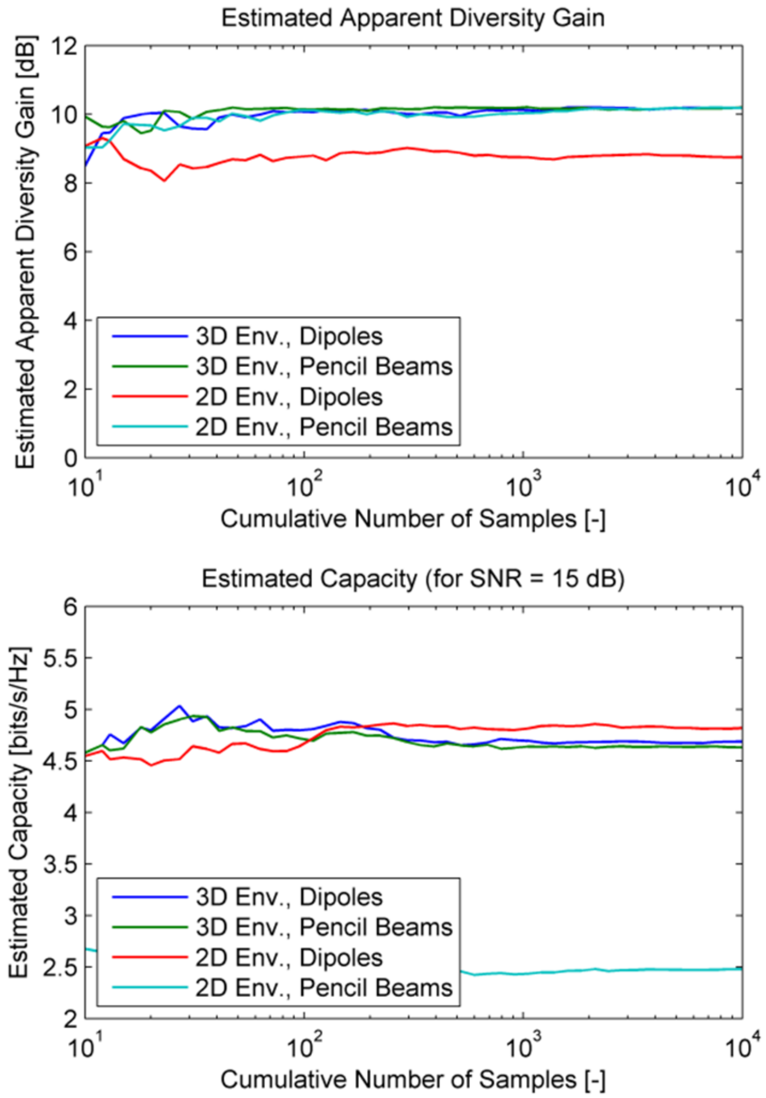

Figure 2.4. Apparent diversity gain (top) and Shannon's channel capacity (bottom) in 3D and 2D multipath environments.

It is already known now that the performance characterization in RIMP environment is independent of the position and orientation of the antenna. But the performance characterization in LOS is always dependent on the position and orientation of the antenna. This means that the random orientation and position of the mobile terminal will eventually make the LOS component random. Here, for simplicity, we can assume that the LOS contribution will be complex Gaussian distributed. Since both LOS and NLOS contributions are complex Gaussian, then the CDF of the resulting voltages at the antenna ports will follow Rayleigh distribution as well. This is shown in Fig. 2.5 where we see CDFs of received voltages at four ports of an ideal multiport antenna and CDFs of MRC-combined diversity channel of a 4×4 MIMO system. We see that the CDFs follow ideal Rayleigh fading distribution although we have a Rician fading environment with a random LOS-component having complex Gaussian distribution.

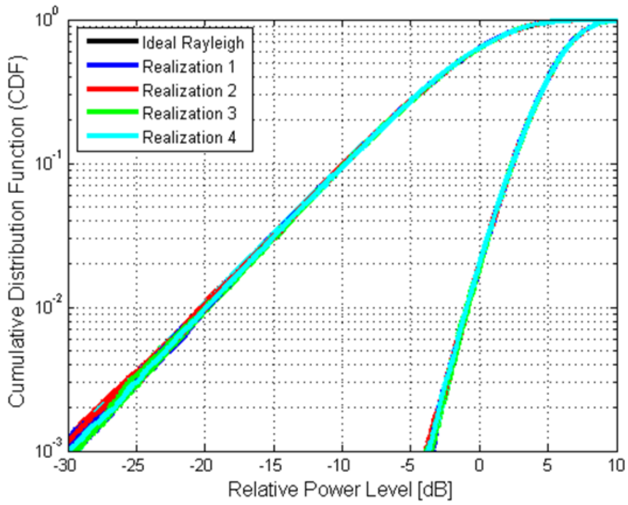

Figure 2.5. CDFs of 4×4 MIMO system with MRC-combined signal in Rician fading with complex Gaussian distributed LOS component and Rician K = 3 dB.

It has been concluded in [40] that the CDF of Rician fading with LOS-component having complex Gaussian distribution converges to the CDF of ideal Rayleigh distribution. Therefore, under these conditions there remains no need to emulate Rician fading environments for OTA testing of wireless mobile devices; they can be tested in Rayleigh fading.

CHAPTER 3 3D-Random Pure-LOS

Traditionally, LOS channel is known as fixed and deterministic channel. Here, we are assuming that the environment between the LOS antennas is not changing. It is true that pure LOS channel is deterministic for fixed antenna systems e.g. microwave links, TV transmission, satellite communication, etc. The position and orientation of these antenna systems are fixed and as a consequence the phase, amplitude, and polarization are fixed for this system.

In contrast, when we talk about mobile terminal users, the channel is NLOS which is mostly neither fixed nor deterministic; it is varying randomly with space, frequency, and time. These users are mostly indoors e.g. home, office, shopping center, etc. where there are many moving and scattering objects around the mobile terminal. The NLOS channel becomes random in phase, amplitude, polarization, and angle-of-arrival after experiencing different phenomena such as reflection, diffraction, and scattering, etc. The most commonly used distribution for modeling such NLOS channels is Rayleigh distribution.

Although the mobile terminals are most often present in scattering environments but still there exist possibilities in which these mobile terminals are present in pure-LOS e.g. mobile terminal users very close to the micro base station in a non-scattering environment. Now we question ourselves if this pure-LOS channel will look like the traditional LOS channel which is fixed and deterministic. Yes, it is fixed and deterministic LOS channel only if the position and orientation of the terminal is not changing. In reality, the user is not fixed in position and orientation. We argue that different random positions and orientations of the terminal will change the deterministic LOS channel to a random LOS channel. Different users in a pure-LOS environment having different positions and orientations of the terminal will experience a completely different random channel. We simulate the 3D-random pure-LOS model by using a single incoming LOS wave with fixed amplitude, uniformly distributed phase, angle-of-arrival, and polarization angle. The randomness in the LOS-component of the channel has been presented for diversity gains in [1]; for capacity of mobile multiple-antenna wireless link in [41]; for MIMO OTA-tests in Rician fading in [40].

From illustration in Fig. 3.1 the randomness in LOS due to orientation of the terminal is easier to understand. The random position of the terminal makes the phase of the incoming wave to appear random. The random orientation of the terminal makes the angle-of-arrival of the incoming wave and the polarization-angle to appear random at the mobile terminal antenna.

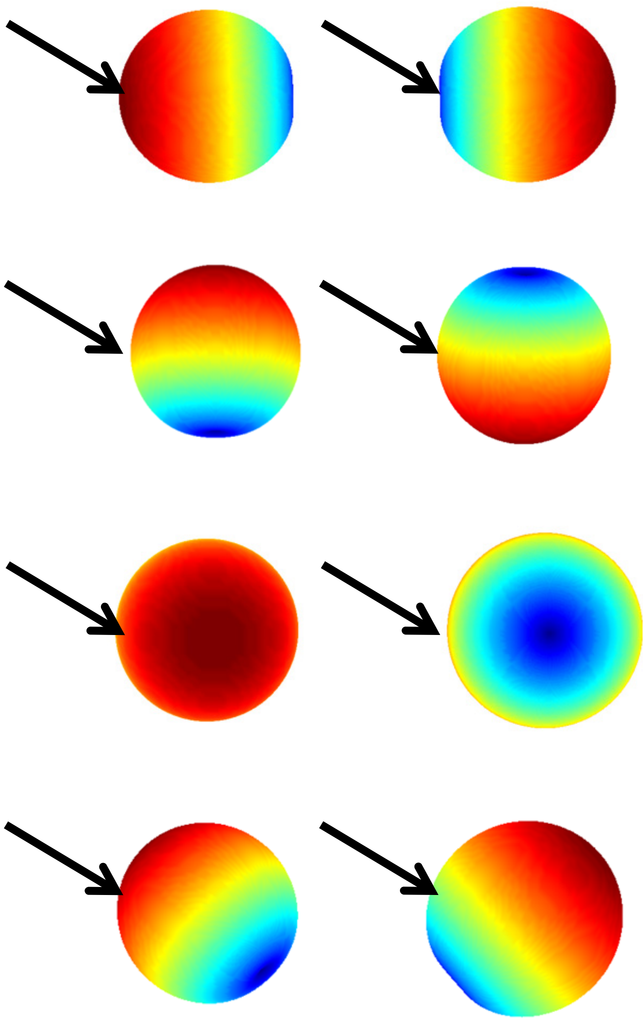

Figure 3.1. Illustration of random orientation of the Huygen's source in the presence of LOS.

The results in Fig. 3.2 show CDFs of a two-port antenna on a mobile phone mockup and its MRC-combined diversity channel. Originally, the diversity gain was defined for single moving user in a RIMP environment, typically at 1% CDF level. Recently, the diversity gain is defined for a bunch of users with 3D random orientation and position of the mobile terminal in random-LOS [1], typically for 1% users with worst performance. From results, it can be observed that antennas with regular shape far-field patterns, e.g. dipole antennas, in random pure-LOS do not follow ideal Rayleigh distribution. In reality, the far-field patterns are irregular in shape due to the effect of user head, hand, etc. and therefore will more likely follow Rayleigh distribution.

From an illustration in Fig. 3.3, it is shown that the orientation of the phone with respect to the environment is not fixed. A user holding a phone on right side of the head shows marked arrow in a horizontal direction. The direction of this arrow becomes vertical when the user tries to hold it on the left side of the head instead. This means that the LOS-component is fixed in the coordinate system of the environment but the orientation of the mobile terminal is 3D random which makes the LOS-component appear random as well.

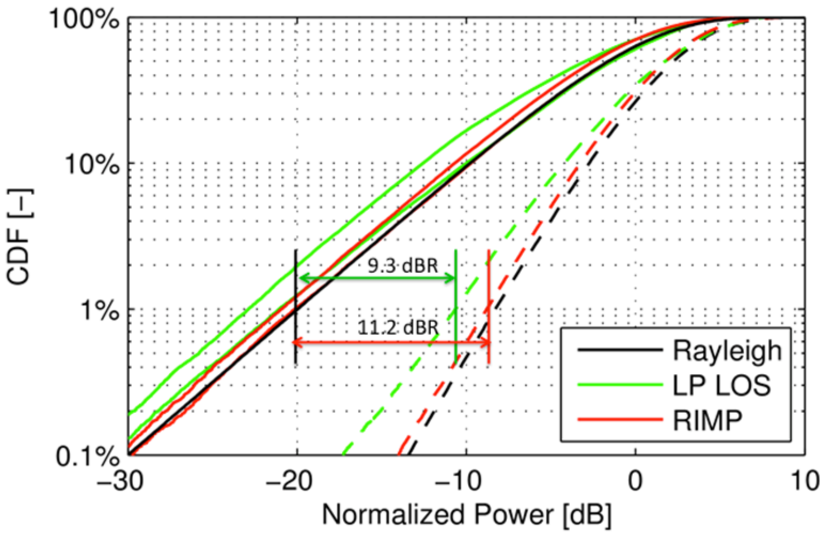

Figure 3.2. CDFs of two-port diversity antenna in RIMP and linear polarized random-LOS.

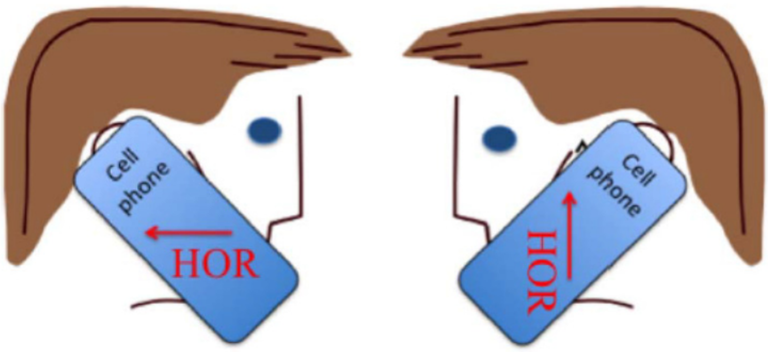

Figure 3.3. A user holding a phone with a marked arrow shows that the direction of arrow changes from horizontal to vertical when holding the phone from right (left) to left sides (right).

The diversity gain in 3D-random pure-LOS is defined in terms of dBR i.e. diversity gain with reference to ideal Rayleigh CDF, typically defined at 1% CDF-level. This is shown in Fig. 3.2.

This study of random pure-LOS can be extended in future e.g. by studying diversity gain and capacity for LTE MIMO terminals.

CHAPTER 4 Simulation Tools

Simulation tools are quite essential to try and test new ideas e.g. random-LOS and to validate established ideas e.g. RIMP environment model. They provide cost effective method to convey useful information in a pedagogical way especially when OTA system performance of a mobile-terminal depends on many different parameters which are dependent on each other. At Chalmers University, we have developed two different multipath simulators i.e. Rayleigh-lab and ViRM-lab.

The Rayleigh-lab is based on random number generator and simulates the resulting complex voltages at the antenna ports in a Rayleigh fading environment. It is used as a simple pedagogical tool for studying convergence. We can study convergence of efficiency, correlation, CDFs, diversity gain, and capacity of a MIMO system. The simulation tool provides a user-friendly graphical user interface (GUI), as shown in Fig. 4.1. The GUI allows user to input different parameters e.g. embedded element efficiencies and correlation to calculate diversity gain. The study of standard deviation in the measurements of diversity gain, capacity, etc. is also studied using Rayleigh-lab.

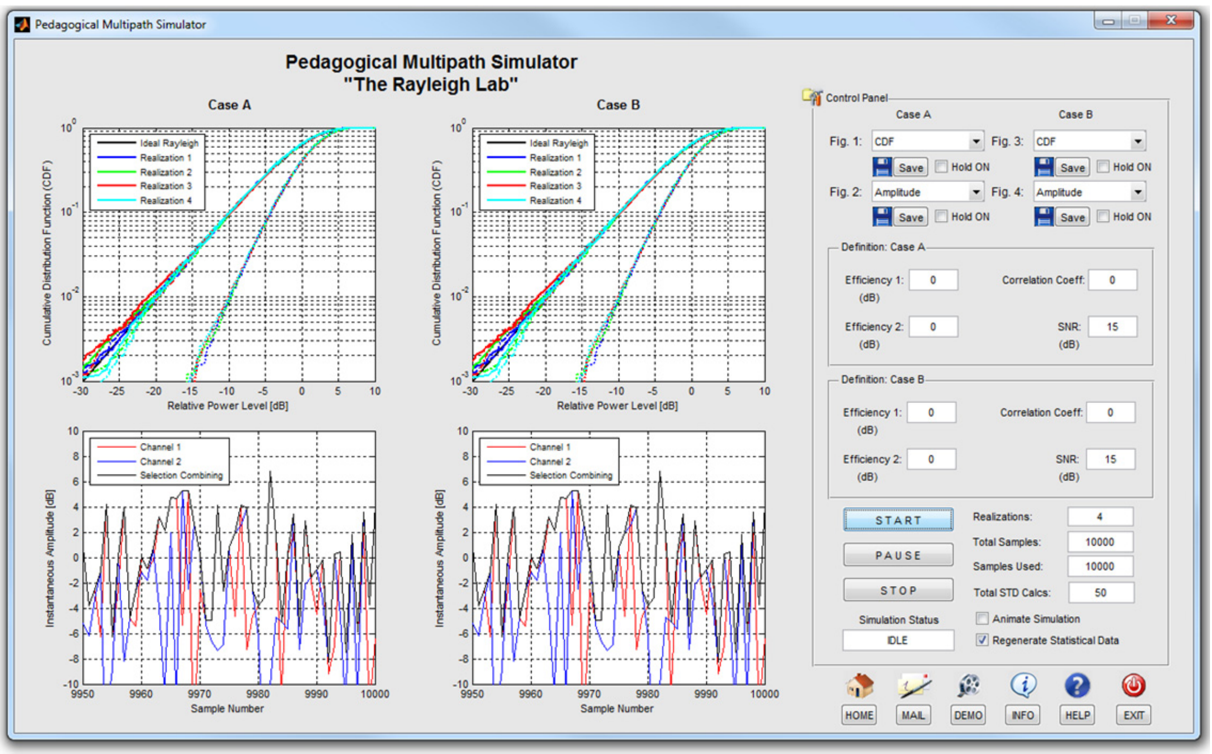

Figure 4.1.Snapshot of GUI of a pedagogical multipath simulator - Rayleigh-lab.

The ViRM-lab is a ray-based simulation tool which is also coded in MATLAB. This tool uses antenna far-field patterns and simulates RIMP environment. Different studies including the comparison of 2D and 3D multipath environments, random-LOS, etc. are done using this tool. The far-field patterns from different EM simulation software such as CST MWS, HFSS, etc. as well as measured patterns from anechoic chamber can be imported into ViRM-lab. The procedure to run a multipath simulation using functions built-in ViRM-lab can be understood by flowchart shown in Fig. 4.2.

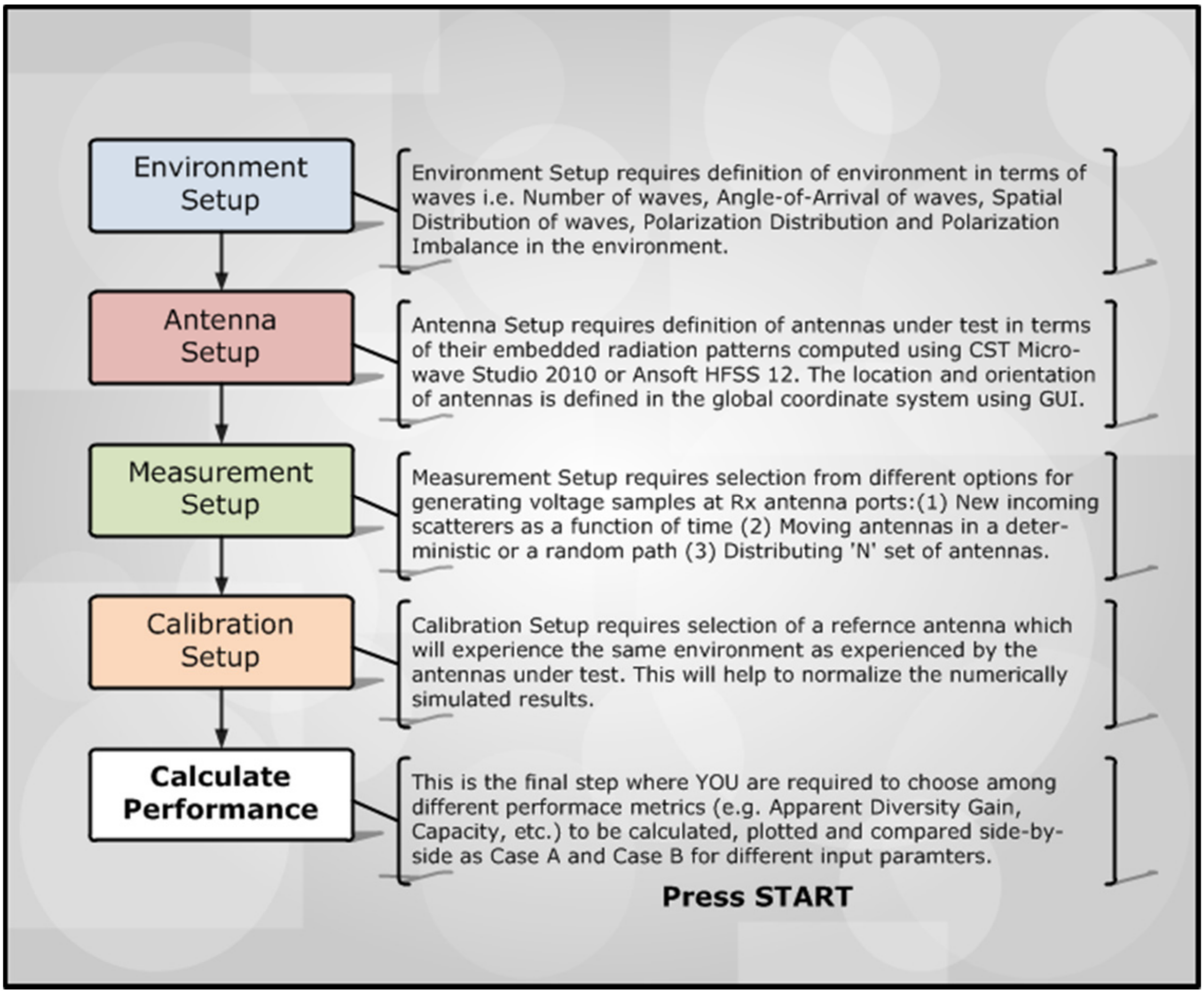

Figure 4.2. Flow chart of a ray-based multipath simulation tool – ViRM-lab.

Firstly, the environment model is defined to simulate e.g. RIMP, 3D random LOS, etc. An environment is setup by defining number of incoming waves, AoA and distribution of AoA of these waves, polarization distribution and polarization imbalance, amplitude and phase of the incoming waves, etc. Secondly, antenna setup is performed by loading the embedded far-field patterns of the antenna into ViRM-lab and by defining the location(s) and the orientation(s) of the antenna(s) or mobile terminal(s). Thirdly, the measurement setup is defined by defining number of samples to be simulated on each antenna port of a multiport mobile terminal as a function of (i) time, or (ii) random or deterministic positions and orientations in space, or (iii) number of mobile terminals, etc. Fourthly, the simulated complex voltage samples at the antenna port are calibrated by normalization e.g. by using isotropic antenna as a reference antenna for calibration. Finally, a performance metric of interest e.g. efficiency, correlation, diversity gain, capacity, throughput, etc. can be chosen for evaluation. This can help us to compare performance in different multipath environments e.g. 2D and 3D multipath environments as well as to compare performance of different antennas in a multipath environment e.g. dipoles and pencil-beams in RIMP environment.

CHAPTER 5 Threshold Receiver Model for Throughput of Wireless Devices with MIMO & OFDM

Today LTE is the latest telecommunication standard for mobile phones after its predecessors GSM and WCDMA. The main advantage of using LTE is higher throughput where MIMO and OFDM diversity gains contribute. The flexibility to choose modulation scheme, bandwidth, block size, code rate, MIMO-multiplexing or MIMO-diversity has made the system quite robust to adjust to the environment in different SNR-regimes. On the other hand, this makes the system design also complicated. A simple theoretical model based on threshold receiver model to simulate the OTA throughput performance of the LTE device is presented. The simulated results have good agreement with the measurements of a commercially available LTE device, performed inside reverberation chamber [18].

This model is very simple and includes the effect of spatial-diversity (i.e. MIMO) and frequency diversity (i.e. OFDM). The model is shown in (5.1) below:

$$T = R \times CCDF(P_t/P_{av}) \tag{5.1}$$

$$CCDF(P_t/P_{av}) = 1 - CDF(P_t/P_{av}) \tag{5.2}$$

$$CDF(P_t/P_{av}) = \int_0^{P_t} pdf(P/P_{av})\, dP \tag{5.3}$$

Here, T is throughput, R is maximum achievable data-rate, P_t is threshold power, P_{av} is average received signal power by the terminal, P is the received signal power, pdf is the probability density function, CDF is cumulative distribution function, and $CCDF$ is complementary CDF.

In our study, the threshold power P_t is always a measured quantity and it is fixed for a given system configuration and for a given receiver terminal. It is measured in an AWGN channel (i.e. no fading) by connecting a cable directly between the external antenna-port of the LTE terminal and the LTE base-station. The measurement setup is illustrated in Fig. 5.1.

To use (5.1) for estimating the OTA-throughput of an LTE device, we need to calculate the $CCDF$ of the MRC-combined diversity channel, which includes spatial diversity due to MIMO and frequency diversity due to OFDM. The total number of channels to compute the $CCDF$ of the diversity channel is known simply by multiplying number of frequency diversity channels N_{fd}, number of transmit antennas N_t, and number of receive antennas N_r as shown in (5.4). The number of frequency diversity channels N_{fd} is calculated simply by taking the ratio of system bandwidth and coherence bandwidth as shown in (5.5).

$$N_{total} = N_{fd} \times N_t \times N_r \tag{5.4}$$

$$N_{fd} = B_s / B_c \tag{5.5}$$

The larger the coherence bandwidth B_c, the larger will be the frequency diversity N_{fd} for a given system bandwidth B_s and vice versa. Similarly, the larger the system bandwidth B_s, the larger will be the frequency diversity N_{fd}. But larger system bandwidths B_s requires higher SNR to support higher data-rates.

The measurement setup for both conducted measurements and OTA measurements is shown in Fig. 5.1 below:

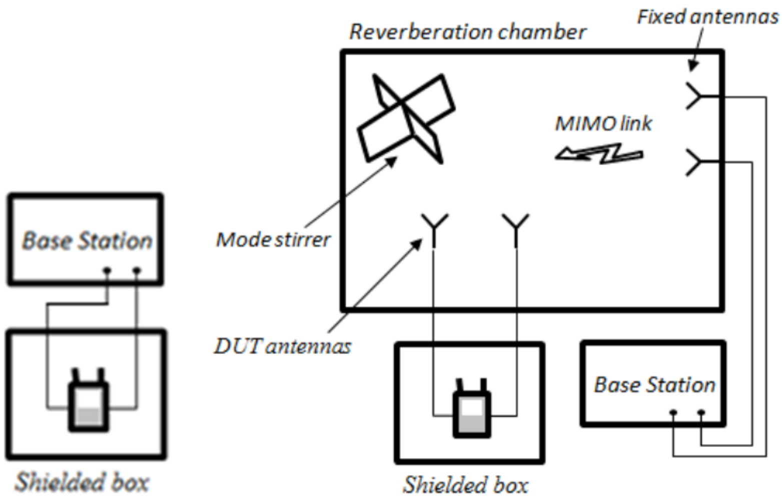

Figure 5.1. Conducted measurement setup (left) and OTA measurement setup (right)

The model has been tested for both different coherence bandwidths and different system bandwidths in [19], also shown in Fig. 5.2. The coherence bandwidth of the channel inside reverberation chamber is controlled by lossy objects inside the reverberation chamber. The relationship between coherence bandwidth B_c and delay spread σ inside reverberation chamber is shown below [29]:

$$B_c = \sqrt{3}/\pi\sigma \tag{5.6}$$

In Fig. 5.2 we can see that the OTA throughput is increasing with the increasing average power. Also, the slope of the throughput curves (representing the frequency diversity) is different for different coherence bandwidth B_c for given system bandwidths B_s. The results show LTE throughput of 2×2 MIMO using transmit-diversity for fixed 64-QAM modulation scheme. In reality, the modulation scheme is adaptable and not fixed. The higher modulation schemes such as 64-QAM is supported at higher power levels, and lower modulation schemes such as 16-QAM is supported at lower power levels. There is no LTE base station simulator available yet which can provide adaptable modulation schemes.

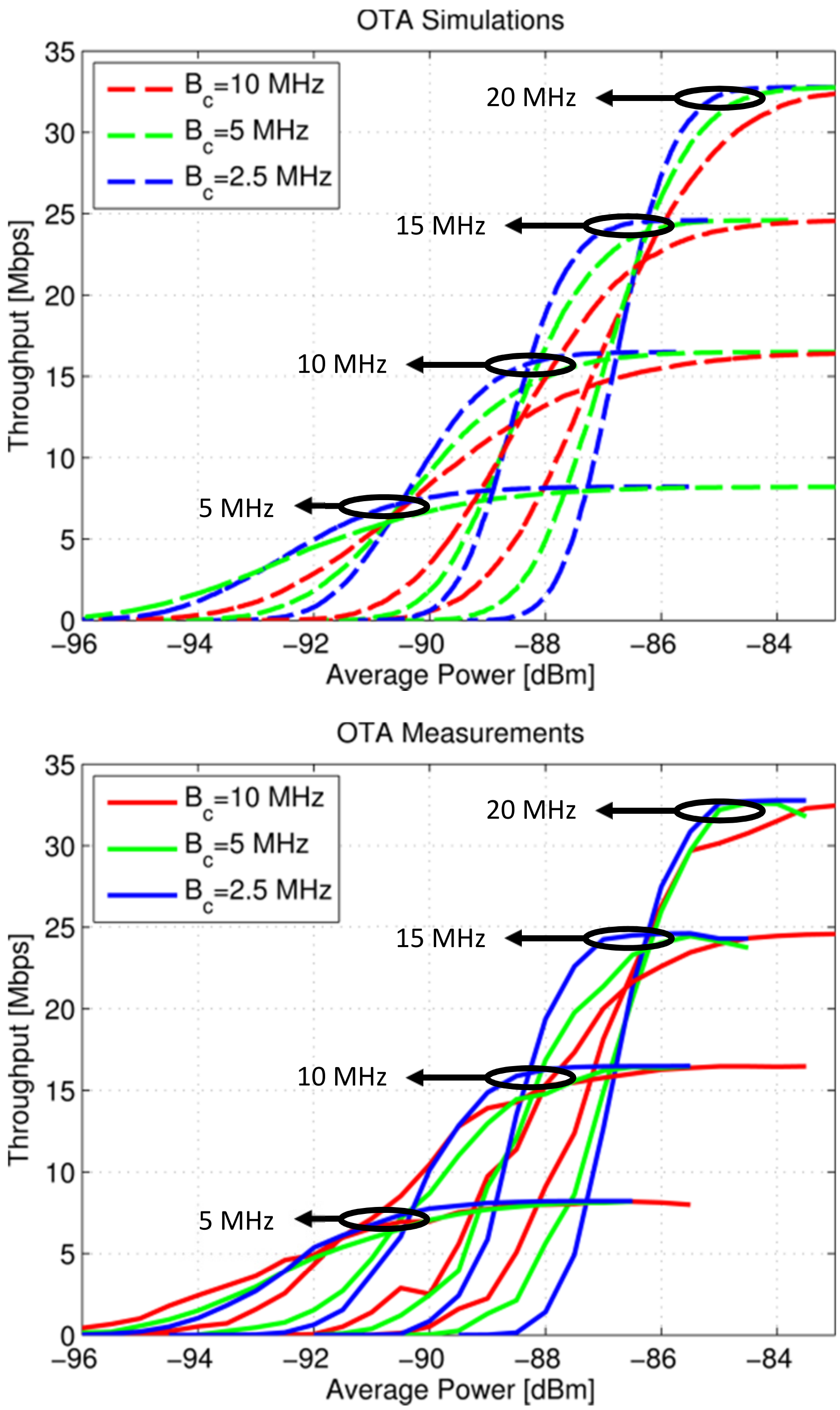

Figure 5.2. OTA-simulations (top) and -measurements (bottom) of 2×2 MIMO LTE throughput for system bandwidths of 20, 15, 10, and 5 MHz; coherence bandwidths of 10, 5, and 2.5 MHz.

The proposed model for estimating throughput in (5.1) shows the relationship between CDF and throughput. This relationship can be seen in Fig. 5.3 i.e. diversity gain at 1% CDF-level is the same as the diversity gain at 99% throughput-level.

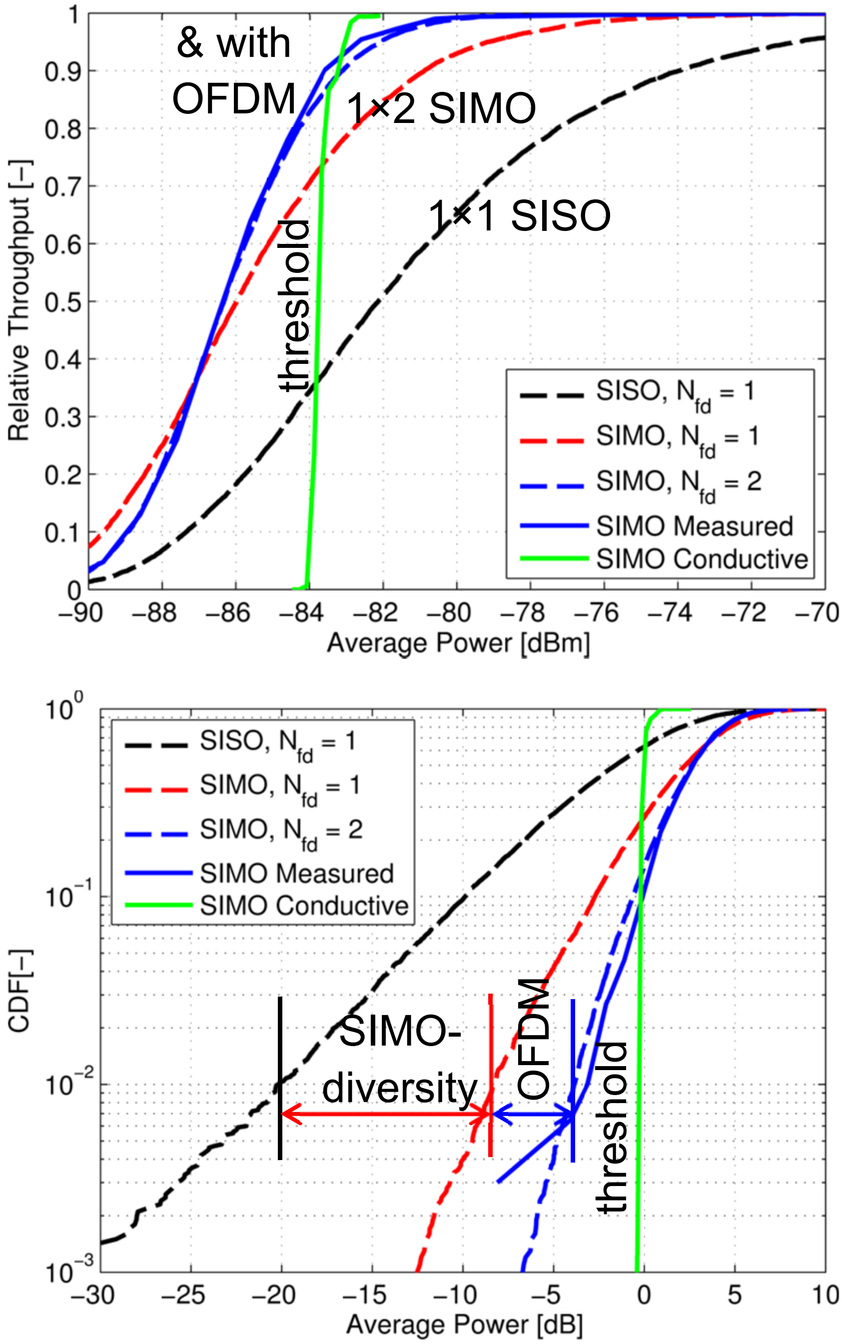

Figure 5.3. Theoretical (dashed) and measured (solid) lines for throughput (upper) and corresponding CDFs (lower) for LTE device with two-port MIMO antenna. P_t= -83.7 dBm.

Similarly, we can model LTE throughput of 2×2 MIMO system when each transmit antenna is transmitting a different data-stream i.e. multiplexing as shown in [16]. An illustration of a digital receiver block diagram in 2×2 MIMO-multiplexing configuration is shown in Fig. 5.4. When MIMO is used in spatial multiplexing configuration, parallel data streams can be transmitted over the wireless fading channel. Interference between the data streams can be removed using suitable pre-processing and post-processing techniques.

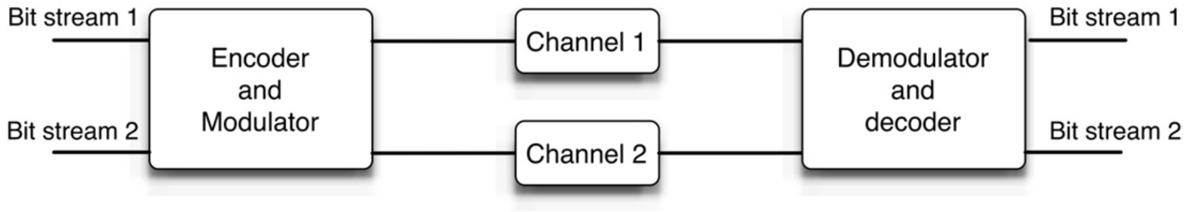

Figure 5.4. Digital receiver block diagram of a 2x2 MIMO system operating in spatial multiplexing configuration.

The throughput in MIMO-multiplexing case is doubled because R the maximum achievable data-rate is doubled now compared to MIMO transmit-diversity case. Since we use two receiver chains, the average of the threshold powers of the receivers P_{tav} will be used as shown below:

$$P_{tav} = \frac{P_{t1} + P_{t2}}{2} = \frac{P_t}{2}\left(\frac{1}{e_1} + \frac{1}{e_2}\right) = \frac{P_t}{2}\left(\frac{e_1 + e_2}{e_1 e_2}\right) \quad (5.7)$$

We have assumed here that both receivers in the MIMO device are the same and their threshold powers P_{t1} and P_{t2} can only vary due to their antenna efficiencies e_1 and e_2. In reality there can be devices which have receivers with dissimilar performances due to differences in the system design and implementation. We leave these complexities for further studies and use our simple formula for estimating throughput of wireless devices which includes the gains due to spatial diversity as well as frequency diversity.

CHAPTER 6 Characterization of UWB Four-Port Bow-Tie Antenna

Recently, an ultra-wideband (UWB) antenna has been developed at Chalmers University of Technology, Sweden. It is a four-port antenna which is an extension of self-grounded bow-tie antenna. It is named bow-tie antenna after its shape which has a resemblance to a bow-tie. The details of design and developments of this antenna and using genetic algorithms for optimization are shown in [37]. A compact size UWB multiport antenna with very low mutual coupling between the antenna ports brings with itself a lot of possible applications and interests in research and development for wireless MIMO communication systems e.g. WiFi, LTE base station, etc. The CST model of UWB four-port bow-tie antenna is shown in Fig. 6.1.

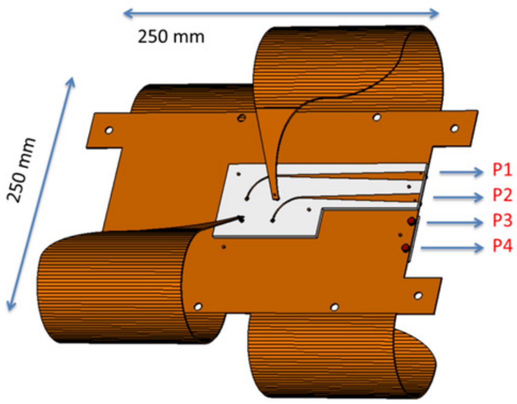

Figure 6.1. CST model of four-port self-grounded bow-tie antenna.

The performance of bow-tie antenna in terms of S-parameters is shown in Fig. 6.2. These S-parameters can be obtained by simulations in CST or measurements of a prototype antenna. The operating frequency range for this antenna is 0.5-16 GHz. The embedded radiation efficiency is defined in [13]. The formulas in terms of S-parameters for embedded radiation efficiency e_{rad} and total embedded radiation efficiency $e_{rad_{total}}$ of embedded element number i when there are total N elements and no ohmic losses, are shown below in (6.1) and (6.2) respectively:

$$e_{rad} = \frac{1-\sum_{j=1}^{N}\left|S_{ij}\right|^2}{1-\left|S_{ii}\right|^2}\ ;\ e_{refl} = 1-\left|S_{ii}\right|^2 \qquad (6.1)$$

$$e_{rad_{total}} = e_{rad} * e_{refl} = 1-\sum_{j=1}^{N}\left|S_{ij}\right|^2 \qquad (6.2)$$

where e_{refl} denotes mismatch efficiency. Since all antenna petals are symmetrical or anti-symmetrical with respect to each other, they have the same radiation efficiency as shown in Fig. 6.3.

The correlation between the ports in a RIMP environment is very low i.e. smaller than 0.1 as shown in Fig. 6.4. This is due to the fact that mutual coupling between the ports is lower than -10 dB; see Fig. 6.2. The correlation can be calculated by using far-field functions [13] or S-parameters. The formula for calculating correlation ρ in terms of S-parameters for an antenna with no ohmic losses is shown in (6.3).

$$\rho_{ij} = \frac{S_{ii}S_{ij} + S_{ji}S_{jj}}{\sqrt{\left[1-\left(\left|S_{ii}\right|^2+\left|S_{ij}\right|^2\right)\right]\left[1-\left(\left|S_{ji}\right|^2+\left|S_{jj}\right|^2\right)\right]}} \tag{6.3}$$

The diversity gains calculated at 1% CDF-level from Fig. 6.5 (left) are plotted in Fig. 6.5 (right) for the whole frequency range which show that there is a clear improvement in the diversity gains of the antenna when we increase the spatial diversity from 2-ports to 3-ports and 4-ports diversity antenna. The improvement is seen over the whole wide bandwidth, which makes this antenna very useful for many practical applications.

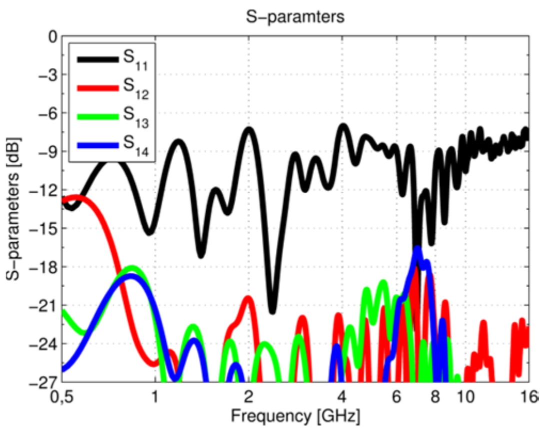

Figure 6.2. Simulated S-parameters of 4-port self-grounded bow-tie antenna from CST.

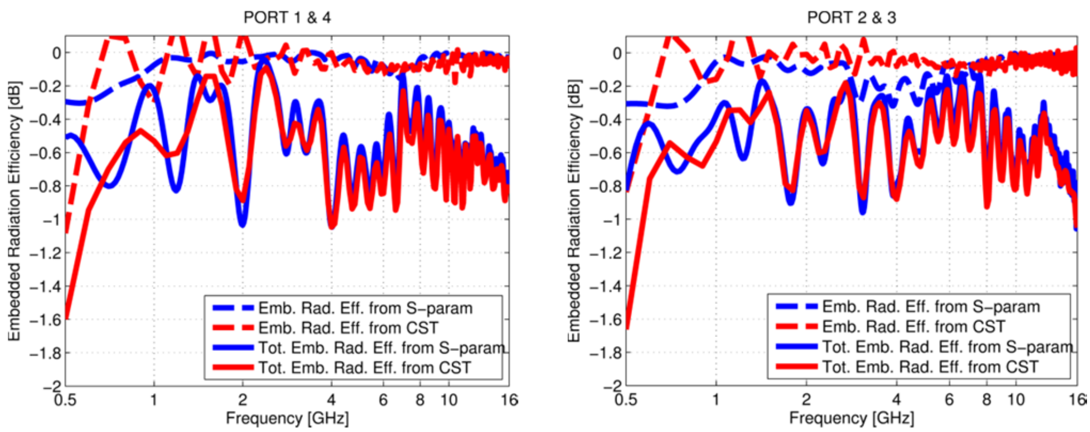

Figure 6.3. Embedded radiation efficiencies of ports 1 &4 (left) and ports 2 & 3 (right) calculated by CST (red color) and calculated by S-parameters from CST (blue color).

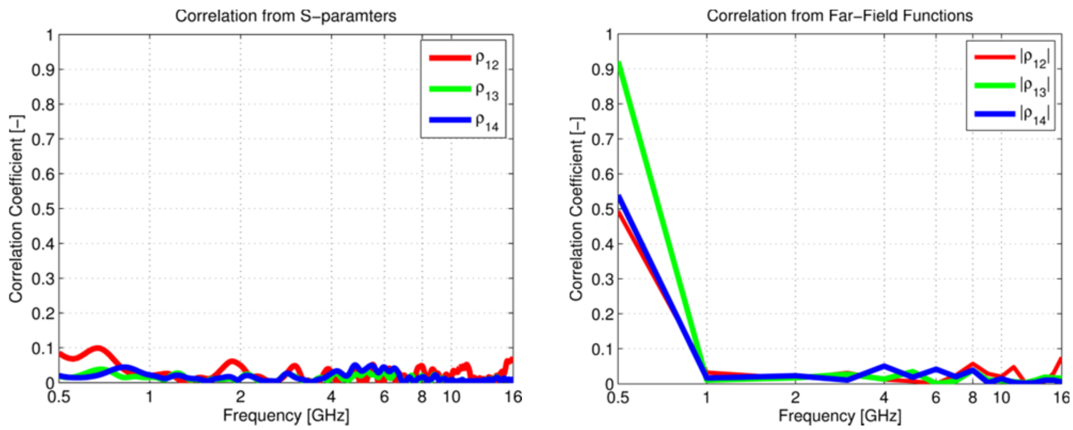

Figure 6.4: Correlations using S-parameters (left) and using embedded far-field functions (right) between port 1 and port 2, 3, and 4.

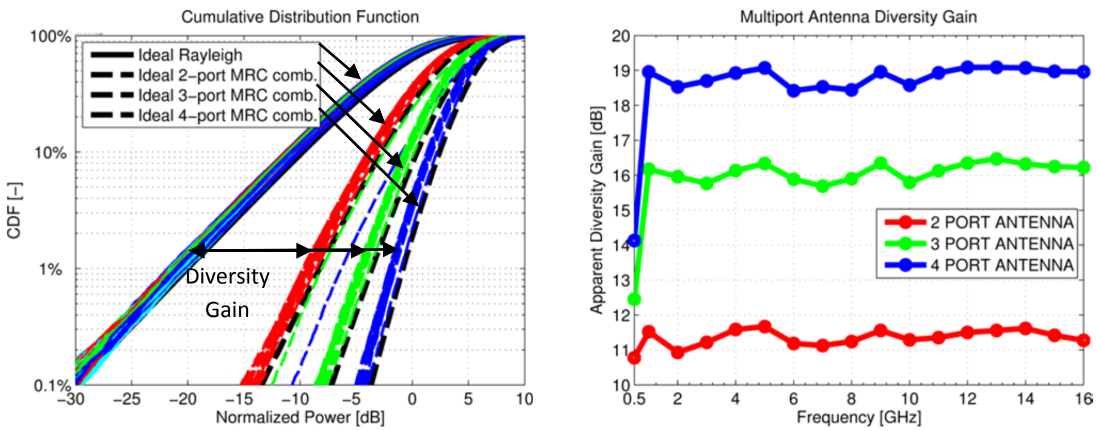

Figure 6.5. CDFs of each antenna port and 2, 3, and 4-port MRC-combined diversity channel (left), and Apparent diversity gains at 1% CDF-level over UWB for 2, 3, and 4-port diversity antenna (right) in RIMP environment.

The antenna diversity gain is quite close to the ideal MRC-combined 2-port, 3-port, and 4-port diversity antennas i.e. 11.7 dB, 16.4 dB, and 19.1 dB respectively. This is due to very high embedded efficiencies as shown in Fig. 6.3 and very low cross-correlation between the antenna-ports as shown in Fig. 6.4.

CHAPTER 7 Characterization of Multiport Mobile Terminal

The performance characterization of single port mobile terminals has been studies a lot during last decades. With the advancement in technology, LTE has become the latest standard for today's communication system using multiple antennas inside an LTE handset. This provides more possibilities to increase data throughput on a mobile phone but on the other hand gives challenges to accommodate more antennas in a limited space. A CST model of a practical two-port mobile phone mockup is shown in Fig. 7.1.

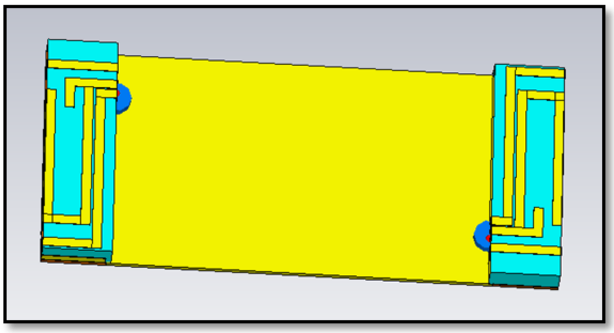

Figure 7.1. A CST model of two-port mobile phone.

The performance characterization of this practical mobile phone model is done using simulations as well as measurements inside reverberation chamber. The simulated S-parameters from CST are presented in Fig. 7.2. The two useful frequency bands are 0.7-1.0 GHz & 1.7-3.2 GHz. The phone mockup is located on both sides of the head according to the standardized talk positions i.e. cheek position and tilt position. The simulated and measured diversity gains on both sides of the head in each talk position are shown in Fig. 7.3. The material properties of head phantom are shown in Table 7.1.

TABLE 7.1. MATERIAL PROPERTIES OF HEAD PHANTOM

Material	**Material Properties**		
	ϵ'	**ϵ''**	**μ**
Head Phantom (Shell)	3.7	0.028	1
Head Phantom (Fluid)	41.33	16.91	1

From results it is observed that the measured and simulated diversity gains have a good agreement in general with the exception of few lower frequency points in tilt position.

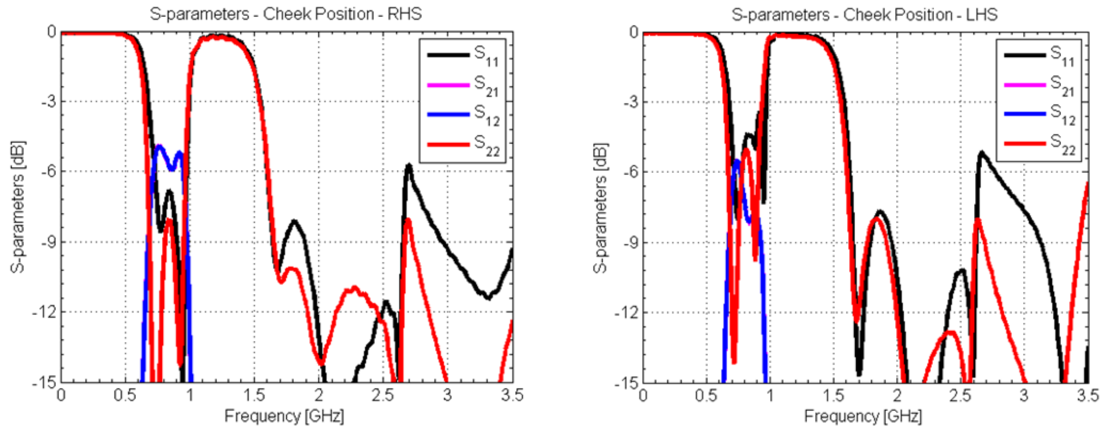

Figure 7.2. Simulated S-parameters of two-port mobile terminal in CST located on right (left) and left sides of the head (right) in the standard cheek position..

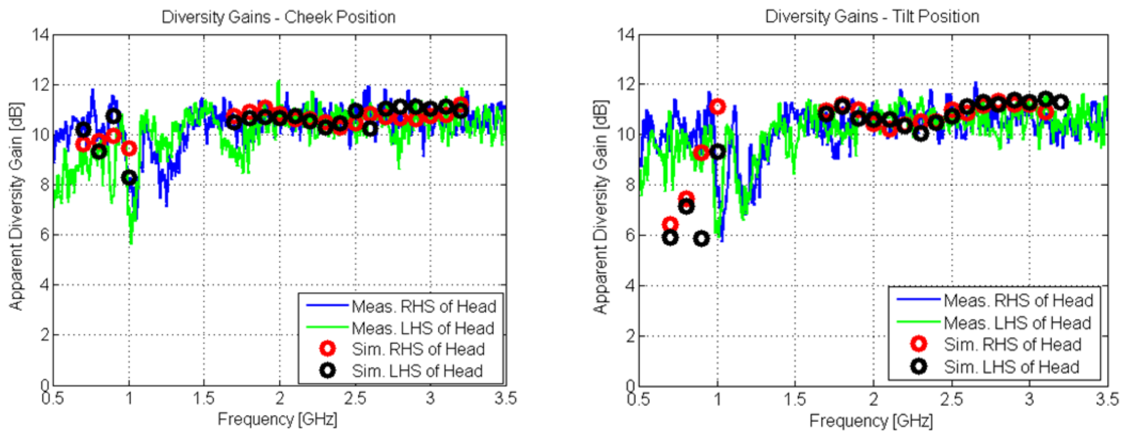

Figure 7.3. Measurements and simulations of diversity gains when two-port mobile terminal is on the right and left side of the head for cheek position (left) and tilt position (right).

Another study about correlation between far-field patterns on both sides of the head was done using the same CST model of two-port mobile phone. The study shows that the correlation between the far-field patterns on both sides of the head is close to 1 i.e. highly correlated when they are presented in the co-ordinate system of the mobile phone. The same patterns show that the correlation is close to 0 i.e. no correlation when they are presented in the co-ordinate system of the environment. In multipath environments such as RIMP, the shape of the radiation pattern does not make any difference. But in other environments such as LOS, the shape of the environment makes a big difference. From Fig. 7.4 we can see that the co-ordinate system which is fixed to the head (or environment) is the same on both sides of the head. The co-ordinate system fixed to the mobile phone has a difference of 90-degrees i.e. vertical direction on one side of the head becomes horizontal on the other side and vice versa.

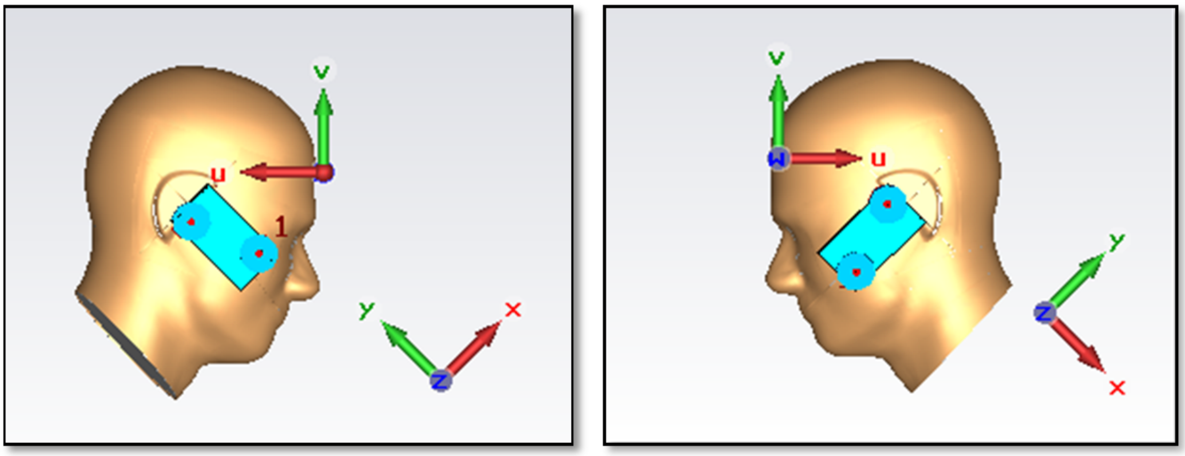

Figure 7.4. A CST model of two-port mobile phone mockup with head phantom.

In Fig. 7.5, the correlation between far-field patterns on both sides of the head is presented together with head and hand phantom and only with head phantom as well.

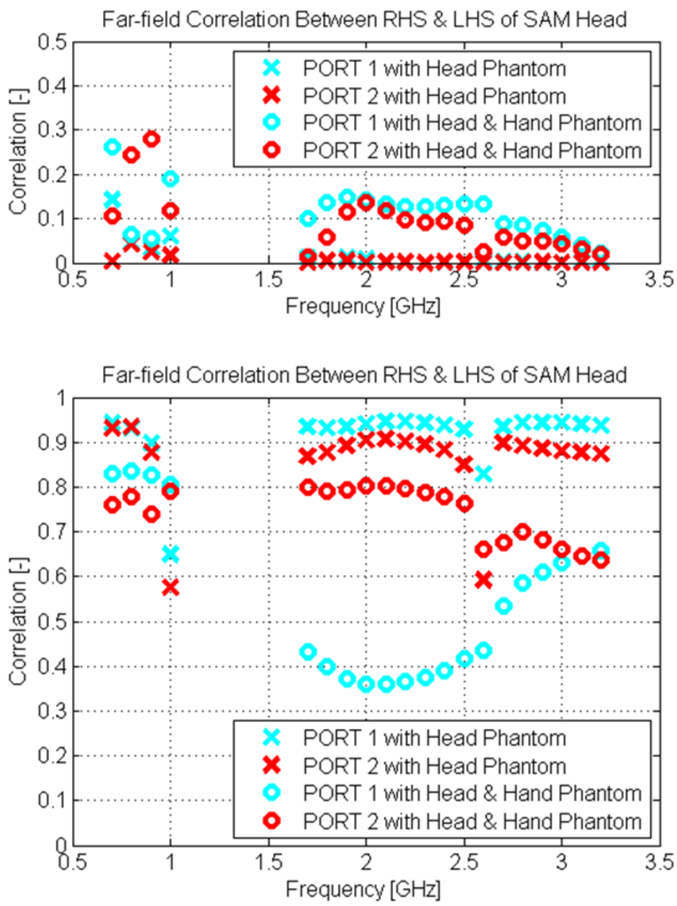

Figure 7.5. Complex correlation between far-field functions on right and left sides of the head when the coordinate system is aligned to the environment (top) and to the terminal (bottom).

CHAPTER 8 Conclusion & Future Work

This thesis is a compilation of results and discussion about using rich isotropic multipath environment as a reference; using randomness of the user in position and orientation; using simulation tools to validate measurements; using simple theoretical models to estimate measured OTA throughput of wireless devices with MIMO & OFDM. In short, this thesis provides arguments in favor of using RIMP and 3D-random pure-LOS as reference environments for characterization of mobile wireless terminals. These arguments are supported very well by human logic as well as by simulations and measurements. At the moment, there is not a single channel model which can define all possible environments for mobile wireless devices. We show that RIMP is an environment which can covers all possible multipath environments and provides unique value for diversity gain, capacity, etc. for any position and orientation of the mobile wireless terminal. We also show that the pure-LOS appears to be 3D-random when considering all possible user positions and orientations of the wireless terminal. Our hypothesis states that the OTA performance of wireless devices in real-life depends on OTA performance in RIMP and 3D-random pure-LOS [42]. Fig. 8.1 illustrates the randomness of the orientation of the mobile wireless terminals.

While some work has already been done to characterize the performance of wireless devices and antennas in multipath environments, there are still many things left to be done in future. Using USRPs in RIMP for different modulations schemes, spatial and frequency diversity, etc. is one of the interesting projects we would like to move forward with in future. Another interesting study is the characterization of LTE MIMO-multiplexing case for wireless devices in RIMP for different LTE system bandwidths and coherence bandwidths. Such studies are of great value and interest for our research to move forward towards more advance problems.

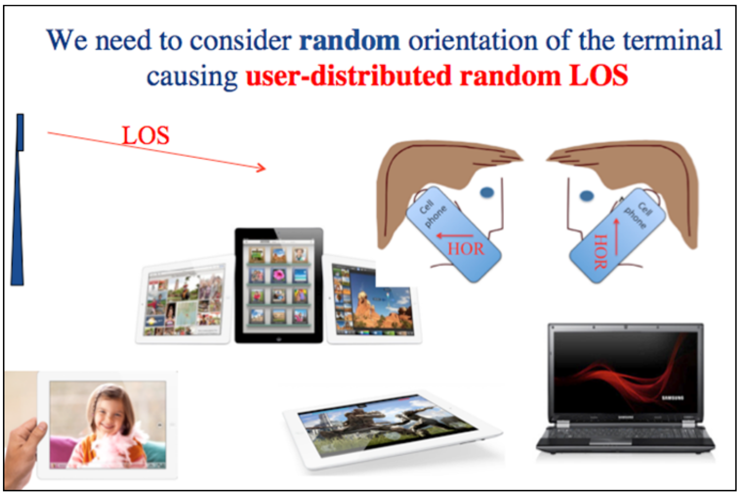

Figure 8.1. Illustration of random orientations of mobile wireless devices e.g. iPad.

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