# Development of a methodology for the assessment of the real-life exposure due to electromagnetic fields

Ashish Rojatkar

## To cite this version:

Ashish Rojatkar. Development of a methodology for the assessment of the real-life exposure due to electromagnetic fields. Physics [physics]. Université Paris-Saclay, 2016. English. <NNT : 2016SACLC028>. <tel-01332611>

HAL Id: tel-01332611
https://tel.archives-ouvertes.fr/tel-01332611
Submitted on 16 Jun 2016

NNT : **2016SACLC028**

# THESE DE DOCTORAT
DE
L'UNIVERSITÉ PARIS-SACLAY
PRÉPARÉE À " **CENTRALESUPELEC** "

ECOLE DOCTORALE N° 575
Electrical, optical, bio-physics and engineering
(Physique et ingénierie : Electrons, Photons, Sciences du vivant)
Spécialité de doctorat : Physique

Par

**M. Ashish ROJATKAR**

# Développement d'une méthodologie pour l'évaluation de l'exposition réelle des personnes aux champs électromagnétiques

**Thèse présentée et soutenue à Gif-sur-Yvette, le 30 Mars 2016**

**Composition du Jury :**

| | | |
|---|---|---|
| M. Lesselier Dominique | CNRS | Président |
| M. Hélier Marc | UPMC-Paris | Rapporteur |
| M. Joseph Wout | Ghent University | Rapporteur |
| M. Monebhurrun Vikass | CentraleSupélec | Directeur de thèse |
| M. Gabriel Sami | Vodafone Group | Invité |

# ABSTRACT

The work presented in the thesis is directed towards addressing the requirement for determining the radio frequency (RF) exposure due to mobile phones under typical usage/ real-life scenarios and also to develop a method to predict and compare mobile phones for their real-life RF exposure. The mobile phones are characterized for their specific absorption rate (SAR) and for transmit and receive performance given by the over-the-air (OTA) characterization. Using the SAR and the total radiated power (TRP) characterization, an exposure index referred to as the SAROTA index was previously proposed to predict the real-life exposure due to mobile phones which would also serve as a metric to compare individual phones. In order to experimentally determine the real-life RF exposure, various software modified phones (SMP) are utilized for the study. These phones contain an embedded software capable of recording the network parameters. The study is undertaken in the following order: (a) Characterization of the available tools and resources for performing targeted measurements/experiments, (b) identifying the important radio resource parameters and metrics to perform the targeted measurements, (c) investigation of the actual implementation of the power control mechanism in a live network for various received signal level and received quality environments, (d) investigating the correlation of the over-the-air performance of the mobile phones and the extent of actual power control realization, (e) comparing the actual exposure and the real-life exposure as predicted by the SAROTA index. Based on the logistical and technical challenges encountered, the experiments were restricted to indoor environments to enable repeatability. During the first phase of the study, the stability of the indoor environment was evaluated. During the second phase, the influence of hand phantom on the SAR and TRP of the mobile phones and the capability of the SAROTA index to predict the exposure was investigated. In the third phase, a set of identical software modified phones were externally modified to alter the TRP performance and the methodology to determine the real-life exposure and also verify the capability of the SAROTA index to predict the exposure levels was investigated. The experiments demonstrate that the SAROTA index is capable of predicting the real-life exposure and comparing the mobile phones.

# TABLE OF CONTENTS

**LIST OF FIGURES** ........ **VIII**

**LIST OF TABLES** ........ **XI**

**CHAPTER 1 INTRODUCTION** ........ **1**

1.1 Dosimetry ........ 1

1.2 Exposimetry ........ 4

1.3 RF exposure concerns ........ 7

*1.3.1 Occupational exposures ........ 8*

*1.3.2 Exposure due to base station ........ 9*

*1.3.3 Exposure due to mobile phones ........ 11*

*1.3.4 Biological effects of RF exposure ........ 12*

1.4 SAR Measurement ........ 13

1.5 Over the Air (OTA) Performance Characterization ........ 15

1.6 Overview of power control in GSM and UMTS ........ 18

1.7 SAROTA Concept ........ 20

**CHAPTER 2 CHARACTERIZATION OF MEASUREMENT LOCATIONS** ........ **25**

2.1 Software modified phones ........ 25

2.2 Identification of the measurement parameters ........ 27

*2.2.1 Mobile station power level ........ 28*

*2.2.2 Received Signal Level ........ 29*

*2.2.3 Received Signal Quality ........ 30*

2.3 Preliminary investigation ........ 31

2.4 SAR and OTA Characterization ........ 32

2.5 Uplink Power Control Observations ....................33

2.6 Characterization of indoor environment for a real-life scenario ....................36

2.7 Effect of Hand Phantom on the real-life performance of mobile phones ....................40

2.8 Outdoor Measurements: Stationary Scenario ....................46

2.9 Outdoor Measurements: Mobility Scenario ....................49

**CHAPTER 3 NUMERICAL CHARACTERIZATION OF MOBILE PHONES .................... 53**

3.1 Antenna design and RF exposure ....................54

3.2 Numerical Model ....................58

3.3 Numerical analysis using SAM and hand phantom ....................63

3.4 SAR distribution comparison using flat phantom ....................65

3.5 Designing external modification for the mobile antenna ....................67

*3.5.1 SAR distribution comparison at DCS using SAM phantom ....................69*

**CHAPTER 4 EXPERIMENTAL VALIDATION OF THE SAROTA INDEX .................... 73**

4.1 Selection of DUT ....................78

4.2 Selection of Controls....................81

4.3 Measurements and results ....................81

4.4 GSM 900 MHz band with channel lock ....................82

4.5 Spatial Verification at GSM....................83

4.6 DCS band with channel lock ....................87

4.7 Spatial Verification at DCS ....................88

4.8 Spatial Verification at UMTS is currently under investigation....................91

4.9 Summary ....................93

**CHAPTER 5 CONCLUSION AND PERSPECTIVES .................... 95**

5.1 Conclusion....................95

5.2 PERSPECTIVES....................97

REFERENCES....................99

# LIST OF FIGURES

FIGURE 1.4-I: STANDARD DOSIMETRY TEST SETUP AT CENTRALESUPELEC......15

FIGURE 1.5-I: OTA MEASUREMENT FACILITIES AT CENTRALESUPELEC USING ANECHOIC CHAMBER (RIGHT) AND COMPACT REVERBERATION CHAMBER (LEFT) ......17

FIGURE 1.7-I: HOW SAROTA CONNECTS THE LABORATORY BASED STANDARDIZATION WITH THE REAL-LIFE PERFORMANCE OF THE MOBILE PHONES. ......21

FIGURE 2.5-I: TXLEV FOR THE SAME NETWORK PROVIDER BUT ON DIFFERENT TRAFFIC CHANNELS (TCH) ......35

FIGURE 2.6-I: MEASUREMENT SET UP FOR CHARACTERIZATION OF THE INDOOR ENVIRONMENT......37

FIGURE 2.6-II : AVERAGE UPLINK TRANSMIT LEVEL AND AVERAGE DOWNLINK RECEIVED LEVEL FOR THE FOUR PHONES LOCKED TO THE SAME TCH ......38

FIGURE 2.7-I: SETUP USED FOR COMPARING THE EFFECT OF THE HAND PHANTOM ON THE UPLINK TRANSMIT LEVEL. ......40

FIGURE 2.7-II: AVERAGE UPLINK TXLEV OBSERVED FOR THE GSM BAND ......41

FIGURE 2.7-III: AVERAGE UPLINK TXLEV OBSERVED FOR THE DCS BAND......42

FIGURE 2.7-IV: THE EFFECT OF HAND PHANTOM ON THE RXLEV AT GSM AND DCS WITH BARS ON THE LHS REPRESENT DATA MEASURED WITHOUT HAND AND ON THE RHS WITH THE HAND PHANTOM RESPECTIVELY......42

FIGURE 2.7-V: SARMAX MEASURED WITH THE HAND PHANTOM AND WITHOUT THE HAND PHANTOM FOR GSM AND DCS ......43

FIGURE 2.7-VI: TRPMAX MEASURED WITH THE HAND PHANTOM AND WITHOUT THE HAND PHANTOM FOR GSM AND DCS......43

FIGURE 2.7-VII : THE PREDICTED SAROTA INDEX AT GSM 900 AND GSM 1800......45

FIGURE 2.7-VIII: THE NORMALIZED REAL-LIFE SAR COMPARISON BETWEEN THE PHONE WITH THE HAND PHANTOM AND WITHOUT THE HAND PHANTOM. ......45

FIGURE 2.8-I: OUTDOOR MEASUREMENT SETUP FOR STATIONARY SCENARIO......46

FIGURE 2.8-II: TXLEV COMPARISON WHEN THE MOBILE PHONES ARE OPERATING ON THE CENTER OF THE GSM BAND......47

FIGURE 2.8-III: TXLEV COMPARISON WHEN THE MOBILE PHONES ARE OPERATING ON THE LOWER FREQUENCY OF THE GSM BAND ..47

FIGURE 2.8-IV: TXLEV AND RXLEV COMPARISON FOR MOBILE PHONE WITH AND WITHOUT HAND PHANTOM OPERATING ON THE GSM BAND ......48

FIGURE 2.9-I: OUTDOOR MEASUREMENT SETUP FOR MOBILITY SCENARIO....49

FIGURE 2.9-II: PLOT FOR TXLEV COMPARISON WITH ONE PHONE PLACED USING ELASTIC BAND AND THE OTHER PHONE PLACED USING THE HAND PHANTOM....50

FIGURE 2.9-III: PLOT FOR TXLEV DIFFERENCE WITH ONE PHONE PLACED USING ELASTIC BAND AND THE OTHER PHONE PLACED USING THE HAND PHANTOM....50

FIGURE 2.9-IV: RXQUAL COMPARISON INSIDE THE AUTOMOBILE WITH ONE PHONE PLACED USING ELASTIC BAND AND THE OTHER PHONE PLACED USING THE HAND PHANTOM....51

FIGURE 3.2-I: THE ACTUAL ANTENNA MODULE (LEFT) AND THE PCB (RIGHT) FOR REFERENCE....59

FIGURE 3.2-II : MOBILE PHONE ANTENNA WITH THE GROUND PLANE AND THE RETURN LOSS....60

FIGURE 3.2-III: ANTENNA ALONG WITH THE DIELECTRIC SUPPORT STRUCTURE AND THE RETURN LOSS....60

FIGURE 3.2-IV : COMPONENT VIEW OF THE MOBILE PHONE CAD MODEL AND THE ZOOMED-IN VIEW OF THE TRI-BAND ANTENNA. ..62

FIGURE 3.2-V : THE S11 PROFILE AND THE GSM RADIATION PATTERNS FOR THE MOBILE PHONE CAD MODEL....62

FIGURE 3.3-I: THE NUMERICAL REPRESENTATION OF THE MOBILE PHONE PLACED IN THE RIGHT CHEEK POSITION AGAINST THE SAM PHANTOM USING A HAND PHANTOM....63

FIGURE 3.3-II: RETURN LOSS COMPARISON FOR THE MOBILE PHONE IN FREE SPACE, PHONE PLUS SAM PHANTOM AND PHONE PLUS SAM AND HAND PHANTOM....64

FIGURE 3.3-III: THE RADIATION PATTERN AT 900 MHZ (LEFT) AND AT 1800 MHZ (RIGHT)....65

FIGURE 3.4-I: NUMERICAL MODEL OF THE FLAT PHANTOM AND THE POSITIONING OF THE PHONE....66

FIGURE 3.4-II: THE POINT SAR DISTRIBUTION OF THE REF PHONE AT GSM AND DCS WHERE, (A) MEASURED POINT SAR AT GSM, (B) NUMERICAL POINT SAR AT GSM, (C) MEASURED POINT SAR AT DCS, (D) NUMERICAL POINT SAR AT DCS,....66

FIGURE 3.5-I: THE CAD REPRESENTATION OF DUT1 (LEFT) AND DUT2 (RIGHT)....67

FIGURE 3.5-II: PSSAR DISTRIBUTION FOR DUT1 AT DCS....68

FIGURE 3.5-III: PSSAR DISTRIBUTION FOR DUT2 AT DCS....68

FIGURE 3.5-IV: SAR DISTRIBUTION SIMULATION (TOP) AND MEASUREMENT (BOTTOM) FOR REF....69

FIGURE 3.5-V: SAR DISTRIBUTION SIMULATION (TOP) AND MEASUREMENT (BOTTOM) FOR DUT1....70

FIGURE 3.5-VI: SAR DISTRIBUTION SIMULATION (TOP) AND MEASUREMENT (BOTTOM) FOR DUT2....71

FIGURE 4.1-I: FROM L-R, REF, DUT1 AND DUT2 ........................................ 80

FIGURE 4.3-I: REPRESENTATION OF THE CHARACTERIZED INDOOR ENVIRONMENT USED FOR THE MEASUREMENTS ........................ 81

FIGURE 4.5-I: NORMALIZED SAR AND TRP VALUES OBSERVED FOR THE GSM BAND ........................................ 84

FIGURE 4.5-II: THE AVERAGE TXLEV PERFORMANCE OF THE PHONES AT GSM FOR THE FOUR ORIENTATIONS ........................ 85

FIGURE 4.5-III: NORMALIZED SAROTA INDEX FOR THE GSM BAND ........................................ 86

FIGURE 4.5-IV: NORMALIZED SAR, SAROTA AND SAR_RL VALUES OBSERVED FOR THE GSM BAND ........................ 87

FIGURE 4.7-I: NORMALIZED SAR AND TRP VALUES OBSERVED FOR THE DCS BAND ........................................ 88

FIGURE 4.7-II: THE AVG. TXLEV PERFORMANCE OF THE PHONES AT DCS FOR THE FOUR ORIENTATIONS. ........................ 89

FIGURE 4.7-III: NORMALIZED SAR, SAROTA AND SAR_RL VALUES OBSERVED FOR THE DCS BAND ........................ 90

FIGURE 4.8-I: NORMALIZED SAR AND TRP VALUES OBSERVED FOR THE UMTS BAND ........................................ 91

FIGURE 4.8-II: THE AVG. TXLEV PERFORMANCE OF THE PHONES AT UMTS FOR THE FOUR ORIENTATIONS. ........................ 92

FIGURE 4.8-III: NORMALIZED SAR, SAROTA AND SAR_RL VALUES OBSERVED FOR THE UMTS BAND ........................ 93

# LIST OF TABLES

TABLE 2-1: REFERENCE SENSITIVITY LEVEL FOR DOWNLINK POWER 29

TABLE 2-2: BER TO RECEIVE QUALITY CONVERSION 30

TABLE 2-3: 10G SAR (W/KG) CHARACTERIZATION FOR THE RIGHT CHEEK CONFIGURATION 32

TABLE 2-4: TRP (DBM) CHARACTERIZATION FOR THE RIGHT CHEEK CONFIGURATION 33

TABLE 2-5: SARREAL-LIFE FROM AVERAGE TRPREAL LIFE. 39

TABLE 3-1: SAR 10G AT DCS 72

TABLE 4-1: PREDICTED SAROTA INDEX FOR VARIABLE TRP 75

# ACKNOWLEDGEMENTS

During this Ph.D., I have had the opportunity to discuss and interact with diverse minds and receive suggestions from colleagues and friends at CentraleSupelec. Their support has been a great help in the preparing for the Ph.D. First of all, I would like to express my sincere gratitude to my supervisor Dr. Vikass Monebhurrun and thank him for offering me the opportunity to work on this interesting Ph.D. topic. I am also very grateful to his encouragement, unconditional support throughout my study. I want to thank Dr. S. Ananthakrishnan for training me in the field of RF & Microwaves. I will always be grateful to him for his guidance and insights during my formative years. I gratefully acknowledge the external funding received towards the work presented in this Ph.D. from SFR - France and Dr. Fabrice Lacroux for his encouragement and valuable insights during our eventful discussions.

I want to thank Vincent Polledri for all the technical experimentation support throughout the last three years. It has been an enjoyable experience for me to work with him. I would like to thank the administrative departments of L2S and GEEPS for providing assistance and being extremely helpful and patient during our interactions with my beginner level of spoken French. I would like to thank Dr. Dominique Lesselier for his encouragement and advice relating to research and his insights on the life in France. It has been a pleasure interacting with him on various issues.

I would like to thank my colleagues, Giacomo Rodeghiero, Changyou Li, and Xi Cheng for lively atmosphere in the office and giving me various funny moments to look back upon. I would also like to thank my friends in CentraleSupelec, Alexis Brenes, Andreea Beciu, Daniel Café, Gisela Lechuga, Konstantinos Lekkas, Mickael Brison, Pierre Prache, Pierre Bisiaux, Xu Ming and many more for accepting me into their group and educating me about various customs and traditions of the life in France. I would like to thank Marjolein Verheij for bearing with my occasional aloofness and always encouraging me with a positive outlook and humor.

I would like to thank the members of the jury Dr. Marc Hélier, Dr. Wout Joseph, Dr. Dominique Lesselier and Mr. Sami Gabriel for evaluating my work and providing valuable feedback.

I want to thank my family and my friends back home in India. Special thanks go to my parents who unconditionally supported me in every way possible, for which I am immensely and forever grateful.

# RESUME

Le travail présenté dans cette thèse a pour objectif l’étude des conditions nécessaires pour évaluer l'exposition radio fréquence (RF) due aux téléphones mobiles dans un scenario d’utilisation réelle et le développement d’une méthodologie permettant de prédire et de comparer les téléphones mobiles en fonction de leurs expositions RF réelles. Les téléphones mobiles sont caractérisés par leur débit d'absorption spécifique (DAS) et leur performance en émission et en réception (over-the-air, OTA). En utilisant le DAS et la puissance totale rayonnée (PTR), un indice d'exposition appelée l'indice SAROTA a été proposé précédemment afin de prévoir l'exposition réelle des téléphones mobiles. L’indice SAROTA sert ainsi de métrique permettant de comparer les téléphones mobiles. Afin de déterminer expérimentalement l’exposition réelle aux RF, plusieurs téléphones avec des modifications logicielles permettant d’enregistrer les paramètres du réseau, sont utilisés pour l’étude qui est menée comme suit : (a) caractérisation des outils et des ressources disponibles pour effectuer des mesures ciblées, (b) identification des ressources radio et des paramètres importants pour effectuer ces mesures, (c) étude de la mise en œuvre effective du mécanisme de contrôle de puissance observé dans un réseau mobile réel pour différents niveaux et de qualités du signal reçu, (d) étude de la corrélation entre la performance OTA des téléphones mobiles et l’étendue effective du contrôle de puissance appliquée par le réseau, (e) comparaison entre la valeur réelle de l’exposition et la valeur prédite en utilisant l’indice SAROTA. Comme les défis logistiques et techniques sont plus difficiles à surmonter pour les mesures dans un environnement multi-trajets extérieur, les expériences ont été limitées à des environnements intérieurs pour assurer une meilleure répétabilité des mesures. Lors d’une première phase de l’étude, la stabilité de l’environnement intérieur a été évaluée. Lors d’une deuxième phase, l’influence de la main sur le DAS et la PTR des téléphones mobiles ainsi que sur l’évaluation de l’exposition réelle prédite par l’indice SAROTA a été étudiée. Lors d’une troisième phase, un ensemble de téléphones mobiles identiques ont été modifiés et des mesures effectuées pour

vérifier que l'indice SAROTA permet bien de prédire l'exposition réelle des personnes.

## Introduction

L'exposition RF liée à l'utilisation d'un téléphone mobile près de l'oreille est actuellement caractérisée par le débit d'absorption spécifique (DAS ou SAR, specific absorption rate). Le DAS d'un téléphone mobile quantifie le taux d'énergie radio fréquence (RF) absorbée par le corps lorsque le téléphone émet à la puissance maximale. La valeur du DAS sert essentiellement à établir la conformité au regard de l'exposition de telle sorte que le téléphone mobile vendu dans le commerce ne dépasse pas un seuil de DAS spécifié par les organismes de réglementation. La valeur du DAS mesurée en laboratoire à puissance maximale pour une configuration donnée ne permet pas de déduire l'exposition réelle aux RF. Il est connu que les opérateurs de mobile utilisent un système de contrôle de puissance, pour que le téléphone mobile émette la plus faible quantité de puissance nécessaire pour maintenir une communication satisfaisante. Par conséquent le téléphone n'émet pas toujours à la puissance maximale. Il s'avère néanmoins une tâche délicate de prédire l'étendue du contrôle de puissance et de sa mise en œuvre lorsque le téléphone mobile est utilisé dans des situations diverses. Les opérateurs de réseaux mettent en place différentes stratégies fondées sur la planification RF tels qu'ils fournissent la meilleure qualité de service possible en utilisant l'infrastructure disponible. L'évaluation de la performance du téléphone mobile en terme des capacités d'émission et de réception est donc importante pour les opérateurs pour une gestion efficace du réseau mobile.

Le téléphone mobile est donc également caractérisé pour ses performances OTA (over-the-air), en particulier en terme de puissance totale rayonnée (TRP) et de sensibilité totale isotrope (TIS). La TRP fournit des informations sur la quantité de puissance disponible pour assurer la communication entre le téléphone mobile et l'antenne relais. L'étendue du contrôle de puissance appliqué par la station de base dépend fortement de la TRP du mobile. Par exemple, un téléphone mobile ayant une TRP relativement élevée subira un plus fort contrôle de puissance, résultant en une puissance d’émission relativement plus faible. La performance OTA –TRP et TIS– d’un téléphone mobile joue un rôle important dans la détermination de l’exposition réelle. L’indice SAROTA a été précédemment introduit pour tenir compte à la fois de la performance OTA et du DAS des téléphones mobiles. Il est tout simplement exprimé comme le rapport entre le DAS et la TRP mesurés en laboratoire dans la même configuration : même position du téléphone mobile contre la tête, même canal de trafic et même niveau de puissance d’émission maximale.

$$SAROTA = \left[\frac{SAR}{TRP}\right]_{same\ configuration} \qquad [\mathrm{kg}^{-1}]$$

$$SAR_{real\text{-}life} = SAROTA \times TRP_{real\text{-}life} \qquad [\mathrm{W/kg}]$$

Plusieurs téléphones mobiles avec des modifications logicielles sont utilisés pour évaluer l’exposition réelle dans les bandes Global System for Mobile Communication (GSM 900 MHz), Digital Communication System (DCS 1800 MHz) et Universal Mobile Télécommunication System (UMTS 2100 MHz).

## Méthodologie

Comme le contrôle de puissance est très dépendant des conditions du réseau, il est important de sélectionner dans un premier temps le même opérateur de réseau et autant que possible un environnement électromagnétique relativement stable pour toutes les mesures. Un environnement intérieur a été adopté et caractérisé. L'environnement intérieur est une pièce vide avec son mur de parement extérieur composé presque entièrement de fenêtres en verre. Le niveau du signal reçu dans cet environnement intérieur est considéré comme satisfaisant pour mener les expérimentations et les mesures peuvent être effectuées en fonctionnement avec tous les opérateurs de réseaux disponibles. Les mesures sont effectuées d'une part en configuration espace libre et d'autre part en configuration du téléphone mobile placé dans la position de la joue droite contre le fantôme de tête. Le téléphone mobile et le fantôme sont placés sur une table en bois situél au centre de la pièce. Afin de minimiser les variations dues aux téléphones mobiles, quatre échantillons du même modèle sont choisis et l'environnement intérieur est caractérisé pour les bandes GSM 900 MHz, DCS 1800 MHz et UMTS 2100 MHz.

Un ensemble de quatre téléphones mobiles de même modèle est configuré pour fonctionner uniquement sur un système de communication à la fois (par exemple GSM ou DCS ou UMTS). Afin d'empêcher le téléphone mobile de passer en mode de transmission discontinue (DTX), un appel vocal est simulé en utilisant une fonction du téléphone mobile qui permet de jouer un fichier audio préenregistré. Le fichier audio préenregistré est joué en mode de répétition permettant de simuler des appels de durées courtes et longues, éliminant ainsi la nécessité de tout appareil audio distinct et autres intrusions. Par ailleurs, la fonction de verrouillage du canal est activée afin de forcer la communication sur le canal sélectionné. A la suite d'une analyse préliminaire du niveau reçu (RxLev), de la qualité du signal reçu (RxQual) et de la puissance transmise (TxLev) selon la durée de l'appel variée par séquences de 3, 5, 15 et 30 minutes sur une période de plusieurs jours à différents moments, il est apparu qu'une durée d'au moins 30 minutes est nécessaire pour assurer des mesures stables. Ceci permet d'avoir une estimation conservatrice en moyennant les effets dus aux variations instantanées inattendus dans les paramètres mesurés. Pour chaque mesure il est assuré que la batterie du téléphone mobile est complètement chargée et les mesures sont effectuées en mode voix. La même procédure est appliquée pour effectuer les mesures en utilisant le fantôme de main.

Pour évaluer l'exposition réelle due à différents téléphones mobiles dans l'environnement réel, les caractéristiques radio fréquences –SAR et OTA– de trois des quatre téléphones mobiles sont altérés pour générer des téléphones ayant des caractéristiques différentes. A cet effet, un outil de simulation numérique basé sur une méthode de résolution des équations de Maxwell dans le domaine temporel est employé pour étudier les performances du téléphone mobile qui sert de référence. Le modèle CAO du téléphone mobile n'étant pas disponible, un modèle numérique a été reconstruit en se basant sur les éléments disponibles dans le manuel d'utilisation du téléphone mobile. Des comparaisons entre mesures et simulations –coefficient de réflexion de l'antenne, DAS, diagramme de rayonnement– ont été effectuées pour valider le modèle numérique du téléphone mobile. Par la suite, des modifications ont été apportées au modèle –typiquement en rajoutant des éléments métalliques- autour de l'antenne pour altérer ses caractéristiques. Des modifications correspondantes sont également apportées aux téléphones mobiles pour les mesures, produisant au total quatre téléphones mobiles issus du même modèle mais avec des caractéristiques différentes.

Des mesures d'exposition réelle ont été effectuées dans l'environnement intérieur en utilisant les quatre téléphones pour différentes orientations de la tête -0, 90, 180, 270- afin de prendre en compte les multi-trajets. On observe que lorsque la condition de réception est telle que le niveau de signal reçu est très faible, tous les téléphones émettent à puissance maximale. Par ailleurs, lorsque le niveau de signal reçu est très fort, tous les téléphones mobiles émettent à puissance minimale. Ces configurations ne permettent pas de mettre en avant l'utilité de l'indice SAROTA car dans ces cas, les performances OTA n'influent pas directement sur l'émission du téléphone mobile. Par contre, dans les configurations intermédiaires, le niveau du signal reçu ainsi que la puissance émise varient en fonction des performances OTA. Lorsque la TRP est élevée, un plus fort contrôle de puissance est appliqué au téléphone mobile. De même lorsque la TRP est faible, un plus faible contrôle de puissance est appliqué au téléphone mobile.

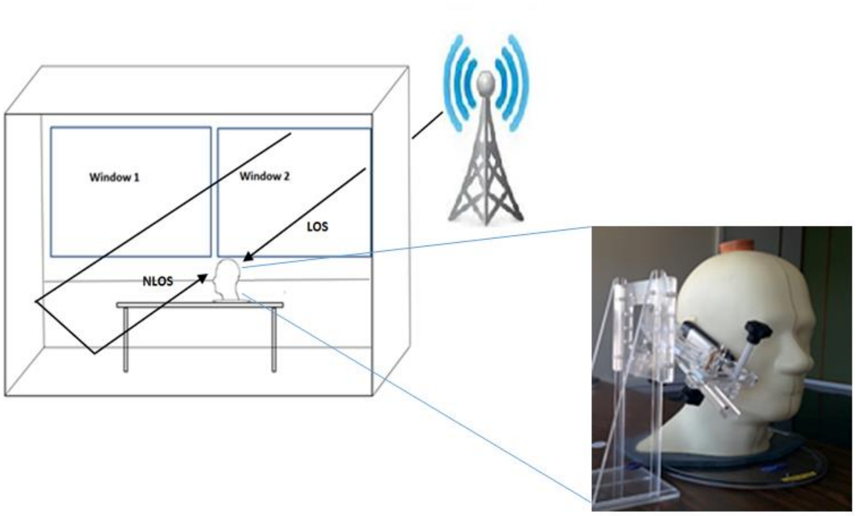


Figure. 1 : L'environnement intérieur

## Conclusion

Avec la formulation SAROTA présente, étant donné un ensemble de téléphones mobiles, l'indice est capable de prédire qui présente de téléphonie mobile d'une exposition de la vie réelle.

# Chapter 1

# Introduction

## 1.1 Dosimetry

Dosimetry in its original sense is the measurement of the absorbed dose delivered by ionizing radiation. With the ever increasing use of wireless technology over the past century for broadcast, communication and medical avenues covering a frequency range (300 KHz to 300 GHz)  the concept was extended to define safety standards for the this frequency range where the effects of non-ionizing radiation could be addressed. The radio frequency (RF) safety standards typically specify the recommendations, guidelines and regulations which outline the basic restrictions and reference levels developed with an objective to protect the human population against potential biological effects. Studies conducted over the past few decades have generated a large amount of data which can now be critically evaluated and categorized to identify observable biological effects. Based on these verifiable effects, the contemporary standards have been developed. As new studies are constantly undertaken, any valuable insight from upcoming research is incorporated after critically reviewing the new data and ultimately the standard is updated.

The objective of the safety standard is to specify a threshold value which can be used as a reference for safety purposes. This threshold value is based on the observed and verifiable effects that lead to a potential health hazard to human beings. Some effects manifest more predominantly than others and have a possibility of a greater impact on the health. The effect that exhibits the most sensitive verifiable response which has a potential to cause health hazards is used to propose a threshold value [1-3]. The possible errors and uncertainties in the measurement process are identified and in order to mitigate these errors and uncertainties, a safety factor or margin is introduced to formulate a working threshold value [1]. The present safety standards and recommendations are a work in progress and have evolved through decades of deliberations by various committees of the American National Standards Institute (ANSI), National Council on Radiation Protection and Measurements, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) [1].

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) was founded in 1992 to address and determine the exposure limits for devices emitting non-ionizing radiation (e.g. mobile phones). Since its inception, guidelines for limiting the electromagnetic field (EMF) exposure for providing protection against known adverse health effects have been one of its main objectives. A distinction is made between health effects which adversely affect the human beings and effects which do not lead to an adverse health effect but are effects which are biologically detectable. Also a distinction is made between the direct and indirect effects caused by the exposure due to EMF. The commission has specified restriction based on the studies and experiments conducted by various research groups across the world.

ICNIRP with consultation and deliberation with various experts has proposed the exposure limits after arriving at a consensus accommodating various differing opinions. The guidelines developed to address the concerns of public health and safety due to RF exposure is based on verifiable scientific data. The commission has established two classes of guidance which are largely reproduced as described in [2]:

- **Basic restrictions:** The restrictions which are established based on the verifiable and known health effects due to exposure to electromagnetic fields are known as basic restrictions. The basic restrictions quantify the limits which should not be exceeded such that protection from the adverse health effect can be achieved. The health effects have been studied and quantified across various frequency ranges and the quantities used are current density, power density and specific absorption rate (SAR). The classification of the quantity is linked to the effect observed. In the frequency range of 1 Hz to 10 MHz, the effects are observed on the functioning of the nervous system and these effects are measured through the current density parameter and therefore the restrictions specified for this frequency range are established on the basis of the current density measurements; the effect of thermal heating in the tissue is observed in the frequency range of 100 kHz and 10 GHz measured through the SAR parameter and between 10 GHz and 300 GHz the thermal heating in the tissue at or near the surface of the body is measured through the power density parameter.

  According to conclusion derived from various studies, the level of temperature rise observed in the frequency range of 10 MHz to a few GHz can be due to the exposure experienced in an environment amounting to a whole-body SAR of 4 W/kg averaged over a period of 30 minutes. This temperature rise can be typically greater than 1°C. A safety factor is generally applied to the quantification at which the effect is observed to account for the errors and uncertainties of the measurement; in this case a safety factor of 5 is applied to establish the limit for the whole-body SAR at 0.4 W/kg for the occupational exposure. The general public is not supposed to be exposed at equivalent levels compared to the occupational exposure scenario. An additional safety factor of 5 is applied to the whole-body SAR limit of occupational exposure and the limit for the general public is established at 0.08 W/kg.

- **Reference levels:** The reference levels are typically established in close relation to the basic restrictions using experimental and/or numerical techniques. The reference levels are often provided to perform an assessment to find the conditions in which the probability of the basic restrictions might be exceeded. Typically, the general public reference levels are lower than the relevant occupational basic restrictions by an adequate safety factor. For example, in the high-frequency range between 10 GHz and 300 GHz, the general public reference levels are lower by a factor of 5 than the occupational exposure restrictions. Both the basic restriction and reference levels are generally conservatively formulated. The compliance with reference levels indicates compliance with basic restrictions.

## 1.2 Exposimetry

The section briefly introduces an important parameter referred to as "exposure" which is closely related to the "absorbed dose" described in the previous section. Exposure describes the amount of radiation energy present in the vicinity of a source of radiation. For the purpose of this study, the reference to exposure is made in terms of the non-ionizing RF and electromagnetic energy available from sources surrounding the general population. The general population is typically exposed to the sources of electromagnetic energy from the broadcast, communication and monitoring technologies. Many expansive studies [4-6], have reported personal RF exposure measurements for various scenarios being conducted in different European countries on 12 frequency bands out of which some are listed below along with some possible emerging technologies which might need close inspection in the near future. The common sources of broadcast technologies are FM radio and television channels in the frequency range between

80 MHz and 850 MHz. The transmission towers are typically located far away from the densely populated areas. The sources of communication technologies however are present in the near vicinity of the general population such as cordless phones (DECT), Mobile phones and base stations for – GSM, DCS, UMTS, 4G/LTE in the frequency range between 700 MHz and 2600 MHz. The adoption of Wi-Fi routers offering Wireless local area networks (WLAN) on the Industrial, scientific and medical (ISM) bands (2400 - 2500 MHz) and (5725 – 5825 MHz) has increased in the past few years. These are found in homes, fast food chains, restaurants, at tourist attractions, at airports and railways stations and also in buses and trains on the move. There is a possibility of more monitoring sources for both indoor and outdoor applications using the Bluetooth, ZigBee and other emerging technologies such as ultra-wide band (UWB) technology (3.1 GHz to 10.4 GHz) are likely become common in the near future.

Exposimetry is the study of measuring the personal RF exposure experienced by the humans in their local surroundings and work places from multiple RF sources. With the increasing and ever changing infrastructure of network of sources of RF radiation, it is a challenging task to perform an RF exposure assessment on a large scale to generate a valuable database of RF energy levels. This database can be used to verify the compliance of various locations to the reference limits proposed by the relevant authorities. The RF exposure assessment can be performed for various scenarios representing indoor and outdoor environments with stationary and mobility circumstances. Valuable insights can be obtained by studying the differences between the RF exposure in indoor environments in a workplace building with a high density of people using mobile phones and a typical household. Similarly the RF exposure experienced by the general population during daily commute with respect to the time taken (it not uncommon for people to spend an average of an hour or two) and the usage of mobile phones either in personal vehicles or public transport will add immensely to the understanding of RF exposure. The work presented in [5] compares personal RF exposure experienced in urban areas belonging to different countries where the following trends for RF exposure were observed: a) the highest exposure is measured for the mobility scenario using public and private transport except for one country where the highest exposure was observed in offices, b) most of the measured scenarios/locations can be typically classified starting from the highest exposure such as public and private modes of transport followed by outdoor areas in an urban region and offices with lowest exposure being observed in urban homes.

The device used for measuring the RF exposure is typically of a standard candybar shaped form factor which can be carried in person in a backpack, mounted on the body using straps and also positioned at important locations at varying heights. The measurement is enabled through a tri-axial probe with a wide bandwidth of operation to capture the levels from as many directions and as many sources as possible. This probe is typically capable of measuring both the electrical and magnetic fields. The probe could be a protruding out of the exposimeters or may be housed within the exposimeters. The probes which are concealed inside the exposimeters are typically realized using printed antenna structures which are easy to integrate on the PCB with the rest of the RF and digital electronics. The exposimeters do need to be calibrated based on the type of measurement i.e. personal exposure assessment or public exposure assessment. For personal exposure assessment, the limitations of using the exposimeter measurement data are discussed in [5, 6] which are related to accurately measuring the exposure near the body and specifically near the head region. This is mostly due to mounting the exposimeter close to the head is not practical for a large population group, the effect of the distance of the exposimeter and the shielding of the body needs to be accounted for in the presence of multiple sources in the vicinity which makes it challenging to isolate the impact of the users' mobile phone. It is a tedious task to meticulously record the activity by a large group of participants. The exposimeter measurement data can be recorded over a period of time and the effect of the movement of the user and their daily activity on the personal exposure can be comprehensively estimated.

## 1.3 RF exposure concerns

The rate at which new technologies using RF have been deployed, the knowledge about the exposure experienced by the general population from the RF sources present in these technologies has not kept pace as more data is required to comprehensively understand the levels and the possible potential to cause effects. A very detailed study [7] presented a detailed review of various epidemiological studies and the health effects due to RF exposure from various sources. Another study published in 2010 [8] has presented the review of the health effects from exposure to RF fields from base stations operating at GSM, DCS and UMTS where the acute symptoms are not observed for majority of the studies. The exposure from these sources is classified as occupational and non-occupational RF exposure. The occupational exposure scenario is considered to be better regulated than the non-occupational exposure scenario with the workers having a functional knowledge of the compliance and safety limits. The knowledge among the general public about the compliance and safety limits of the internal and external sources of RF exposure is typically very limited.

Since the past few years through the print and mass media an effort has been made to increase the awareness about the RF exposure due to mobile phones and the base stations which has also increased the concerns regarding other sources of RF exposure [57]. The radio and TV broadcasting transmitters operate at comparatively higher power levels (up to 1 MW) compared to the power levels (up to 100 W) of mobile phone base stations [9, 10]. However, the radio and TV transmission towers are generally located in sparsely populated areas or sufficiently away from the densely populated urban areas primarily to minimize the exposure to the general public and for the RF exposure purpose can often be excluded from the concerns of the general public. Since the mobile phone usage is continually increasing, the regions with high population density also tend to exhibit a higher density of mobile phone base stations. Comparatively, in the rural regions, the mobile phone base stations are few in number but as the adoption of mobile phone increases along with the usage of voice and data communication, the number of base stations is also likely to increase in the coming few years. Over the past decade, mobile communication infrastructure has evolved considerably. The use of microcell and picocell base stations depending on the site requirement to provide additional capacity in urban areas and to an extent in smaller towns has been increasingly adopted. The microcell base station operates at considerably lower power levels (1 to 2 W). The population exposure assessment will thus have to keep pace with the changing infrastructure landscape.

Various studies have been conducted to assess the potential health effects on the human and animal population. However, the opinion of experts on the quality of the studies varies widely [7]. Many studies have been found lacking in terms of the quality of dosimetry and quality of controls being implemented specially temperature control the effects of which would manifest itself in the tissue heating due to RF exposure. There also exist questions on the extrapolation process often used to map the results from the transgenic model to the human model. Some effects have been reported below the safety limits but these effects have not been classified as adverse health effects. However, based on the existing epidemiological studies, the International Agency for Research on Cancer (IARC) has taken the step of classifying the EMF energy from mobile phones in the class 2B category which implies it is considered as “possibly carcinogenic”.

### 1.3.1 Occupational exposures

The effects due to RF exposure are largely studied at the occupational exposure level where there is a higher likelihood of observing acute responses for various frequency ranges. Workers in certain occupations (e.g. radar operator, RF medical instrument operators, base station technicians etc.) might be more prone to higher and sustained levels of exposure than other occupations [7]. The occupational exposure data is typically obtained from questionnaire based cohort studies where the job description is an important factor is determining exposure. With the regulatory standards in place, it is mandatory that the exposure limits should not be exceeded for any occupationally exposed person working in the presence of electromagnetic fields. The responsibility to ensure this is to be embedded in the workplace policy, operating instructions of RF generating equipment's by the suppliers and manufacturers. Furthermore, using exposimeters, the measurement data generated can be linked to the activity profiles of the workers in certain sensitive occupations. This data based on actual measurements will be more valuable than questionnaire based self-reported data.

### 1.3.2 Exposure due to base station

The exposure due to base stations has been a topic of interest for the past many years as the mobile network has experienced exponential growth. The number of base stations have increased both in the urban and the rural regions. The density of the number of base stations is observed to be higher in the urban regions than in the rural regions largely due to more number of subscribers and a higher population density. The coverage range of base stations in the urban regions is smaller compared to the coverage range in the rural region and with a network of lesser number of base stations in the rural regions, they are required to transmit at a higher power (within the permissible levels) in order to cover a large area. Also in urban areas various microcells and picocells are used to provide enhanced coverage in indoor and high congestion locations.

The exposure assessment due to the base station needs to make a distinction between the rural and urban scenario along with the types of communication systems in use (GSM, DCS, UMTS, 4G/LTE). The exposure due to the base station in an urban region can be complicated with the existence of different types and sizes of buildings and surrounding infrastructure. Typically, the RF levels decrease as the square of the distance from the source (inverse square law). This is largely valid for a big open space with negligible reflections from the surrounding environment enabling line of sight path between the base station and the mobile phones within the network which is often attributed to the rural regions. In an urban region, based on the location of the base station and the surroundings, the communication signals will experience reflection and diffraction leading to superposition of the fields creating regions with high and low field intensity. The field strength levels inside a building can be from 1 to 100 times lower than those observed outside depending on the type of building construction [9]. Additionally, exposure can vary significantly within the building where in some cases the exposure disparity will exist between the upper and lower floors of the same building. Also in the urban areas, it not uncommon to find a diurnal pattern in the exposure from the base stations such that low values are observed night while high values are observed during the rush hours of city life [9].

The exposure form the base stations to general population is different compared to the exposure due to mobile phones. The exposure due to mobile phones is localized largely in the head region or that part of the body nearest to the mobile phone due to the body generally being in the near-field of the energy transmitted by the mobile phone. The exposure due to the base station, on the other hand, leads to a whole-body exposure as the general public is located in the far field region. Since the general public is sufficiently further away from the transmitting source, the intensity of exposure from base stations is typically less than that from a mobile phone. It is worth noting that the exposure from the mobile phones is typically intermittent while that from the base station is continuous.

The exposure due to the base stations is typically measured by performing field strength measurements at specific locations within the coverage region. Periodic recording of the field strength levels increases the accuracy of the estimation of the exposure due to the base stations. The information form the personal exposure measurements performed using exposimeters and the power output data of the base stations can be used in synchronization for the exposure assessment. According to [4], the major contributor towards RF exposure at churches, buildings belonging to schools and kindergartens, outdoor regions and homes were the mobile phone base stations.

### 1.3.3 Exposure due to mobile phones

Considering the ever increasing use of mobile phones across all age groups, it becomes important to study the and possibly quantify the effects of the RF exposure to the users. The guidelines are largely based on the confirmed health hazards due to the thermal effects. There exists little knowledge about the potential health effects due to long-term exposure due to mobile phone usage. The recent studies [4-7] are incorporating the information related to the user activity to generate a better and accurate picture of the exposure patterns. The information about the type of mobile phone used, frequency if usage, intensity of usage, time period of usage, position of the mobile phone, location etc. is crucial to perform a better assessment of the exposure.

This however depends largely on the accuracy of the self-reported accounts and the care being taken that all the important parameters related to transmit and receive performance are accounted for in the analysis. The data recording procedures with the present technology available in the smartphones can be utilized to create automatic logs of the location, time of usage, time period of usage, model of the mobile phone, type of communication network being used, the signal strength and signal quality etc. Other factors useful for the assessment are the usage patterns affecting the RF absorption which is typically observed to be maximum on the side of the head to which the phone is held. Furthermore the RF absorption is dependent on the location and type of the antenna used in the mobile phone and most important, the dynamic power control implemented by the mobile phone operator to vary the transmit power of the mobile phone based on the distance from the base station and the RF channel conditions.

The use of software modified phones for recording transmit and receive levels by the user can resolve some of the issues related to cross-linking the measurements and self-reported data methodology. With the new generation of smartphones, various applications are available which provide information related to the mobile phone model number, the communication technology used, the traffic channel and neighboring channels, received signal level and received signal quality. However most of the applications do not provide the uplink transmit levels. The one that do provide the uplink transmit levels are rather expensive for the common man to purchase but these are within the reach of research groups.

### 1.3.4 Biological effects of RF exposure

The radio frequency exposure due to electromagnetic fields in the frequency range of a few kilohertz to tens of Gigahertz is classified under the non-ionizing radiation category. This implies that the energy of these fields is too low to break chemical bonds or cause the hazardous effects attributed to those due to ionizing radiation from X-rays. There are however established hazards such as the induced thermal heating in the tissues from excessive exposure to electromagnetic fields at high power levels. Since this is largely a non-contact effect, it is also one of the most studied effect of RF exposure. The mere heating of the tissue do not imply an adverse biological effect. Also the heating effect could be seen due to the internal mechanisms of the body and/or due to the physiological strain experienced by the body [7]. As the scientific studies undertaken till have not been able to sufficiently alleviate the concerns, there exists a possibility to further explore the potential hazards due to RF exposure. To address these concerns various research groups, government bodies and private agencies have been involved in funding and conducting research related to explore the possibility of potential health effects due to EMF exposure.

As the sources of RF energy do not cause ionizing effects, many laboratory studies conducted to observe the effect of RF exposure at the cellular level imply there is no direct evidence of RF exposure causing genotoxic effects such as DNA mutations and associated effects [7]. Also studies conducted on animals, specifically on rodents are yet to provide conclusive evidence for the growth of tumors from RF exposure due to mobile phones [10-12].

## 1.4 SAR Measurement

Specific absorption rate (SAR) is the time derivative of the incremental energy (dW) absorbed by or dissipated in an incremental mass (dm) contained in a volume (dV) of a given density (ρ). SAR is more typically considered as an “absorbed dose rate” and is related to electric fields at a point by:

$$\mathrm{SAR} = \frac{(\sigma|\mathrm{E}|^2)}{\rho} \qquad (1)$$

Where: σ = conductivity of the tissue (S/m);

ρ = mass density of the tissue (kg/m3);

E = rms electric field strength (V/m).

For the purpose of compliance testing of wireless devices [13-16], electric field measurements are normally used. The compliance requirements, which apply in general for mobile phones and similar devices such that the SAR values are required to be within the Federal Communications Commission (FCC) and European Union (EU) limits. The limits are specified for the exposure averaged over the whole body and for the exposure averaged over a localized region on the body (e.g. the head). The local SAR is averaged over a volume of tissue defined as a tissue volume in the shape of a cube. The cube should be completely contained inside the volume of tissue to be considered for the averaging calculation. The SAR averaging volumes of 1g and 10g are used for the US and Europe region respectively. In the US, the SAR value is averaged over a 1g cube (IEEE C95.1) as opposed to the 10g of contiguous tissue proposed by ICNIRP for the European region.

The SAR measurement systems typically use two types of phantoms, namely, a cube shaped flat phantom and head shaped specific anthropomorphic mannequin (SAM) phantom the material properties of which are largely based on the values proposed in [17-19]. The SAM phantom structure contains the structural features of the face with ears, nose, lips etc. Also contained are reference lines to enable the standardized positioning of the mobile phones in the typical talk position (right/left cheek position).

International standards such as IEEE1528 and IEC62209 currently specify the measurement procedures for the SAR compliance test of mobile phones. All mobile phones must be tested for SAR compliance before they can be sold to the consumers. The SAR compliance test is conducted in laboratory conditions using the SAM head phantom, filled with the appropriate tissue equivalent liquid while the mobile phone is operated at the maximum power level by establishing a communication link with a base station emulator. The measurements are performed for four intended use positions of the mobile phone against the SAM phantom: right/cheek, right/tilt, left/cheek and left/tilt at the center frequency of a given frequency band. The peak spatial-average SAR –either 1g or 10g– is calculated for each use position which gives the maximum SAR at this frequency band. Two additional measurements are then performed for the two extreme frequencies of the band for the position that yielded the maximum value. The same procedure is applied for all the frequency bands of the mobile phone and ultimately the maximum value obtained from all these configurations should not exceed 2 W/kg averaged over 10g of tissue according to current European SAR regulations. The peak spatial-average SAR value is usually provided by the mobile phone manufacturer or network operator e.g. in the user manual. In France, according to a national decree, all mobile phones are required to display the SAR value for the information of the general public e.g. in the print and media commercials.

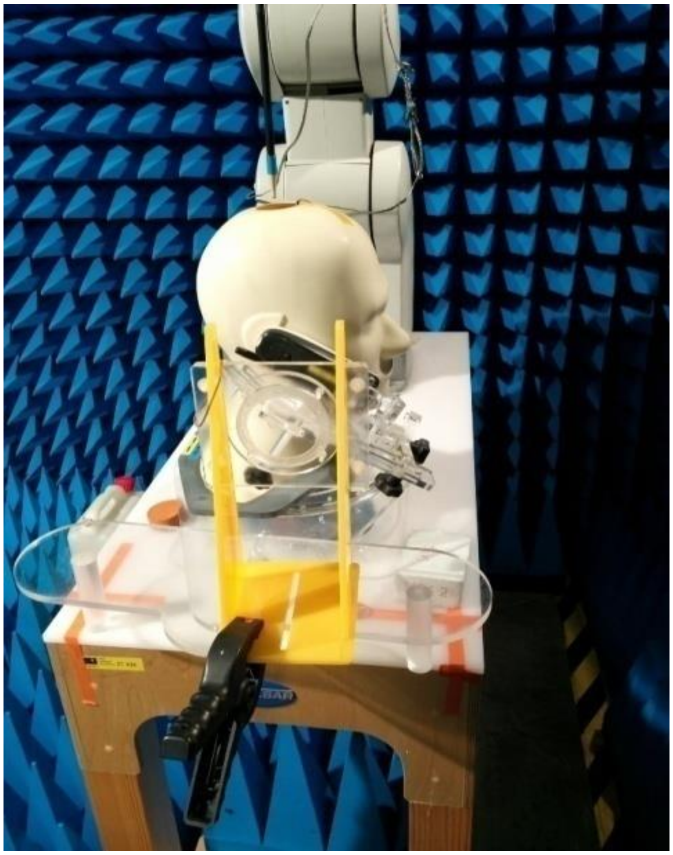


Figure 1.4-i: Standard dosimetry test setup at CentraleSupelec

## 1.5 Over the Air (OTA) Performance Characterization

The mobile phone is a wireless communication device where transmit and receive performance of the device is largely determined by the type of antenna used and its integrated performance in synchronization with the various radiofrequency circuits. Typically the antenna performance is evaluated by measuring its return loss profile to determine the extent of matching across the operating frequency bands and by measuring the radiation pattern to determine the pattern purity and antenna gain. The mobile phone which operates within a cellular network with propagation loss and interference is evaluated in terms of its over-the-air (OTA) performance to better approximate the link budget. This is important as mobile phones with poor OTA performance will generally experience reduced coverage and affect the overall capacity of the cellular network. The OTA performance is generally evaluated in an anechoic chamber according to the test plans described in [20-23]. The OTA measurement can also be performed using reverberation chambers [24, 25].

According to the procedure, the mobile phone antenna is connected to an external signal source through of a coaxial cable. The radiation pattern is then measured for the mobile phone antenna in the presence of the coaxial cable which can pose a metallic near field impairment capable of altering the radiation pattern of the antenna. Also there is a possibility of currents being induced on the coaxial cable leading to spurious emission. The accuracy of the measurement is to an extent degraded as efforts must be made to reduce the spurious emissions from the coaxial cable and the proximity effects on the antenna. This type of measurement where the antenna performance without the influence of the RF circuits is evaluated is referred to as a passive (conducted) measurement method.

To overcome the drawback of the passive OTA measurement method, the active (radiated) measurement method can be used. In this method, instead of an external source exciting the antenna through a coaxial cable, the RF transceiver section is used as an internal signal source by establishing a radio link with a base station emulator. Since the coaxial cable is not present in the setup, the issue of spurious emission and near field effects inherent in the passive measurement method is avoided which increases the accuracy of the measurements. With the active method, the performance of solely the antenna section cannot be measured but the effect of the matching between the integrated RF sections which is referred to as the overall radio performance of the mobile antenna terminal. The overall radio performance is evaluated in terms of two figures of merit, the total radiated power (TRP) which indicates the maximum power available for communication available for the uplink from the mobile terminal and the total isotropic sensitivity (TIS) which signifies the lowest received power in the downlink for a specified bit error rate (BER).

The passive (conducted) measurement method has a limitation in terms of measurement of the performance of the mobile phone in the presence the head phantom and hand phantom. The presence of the coaxial cable would introduce errors in accurately positioning the mobile in the recommended positions. It was largely suited for the performance evaluation of the antenna section. The active (radiated) measurement method is observed to be suited for the OTA characterization of the mobile phone in the presence of the head and hand phantom. The active measurement method evaluates the performance of the mobile terminal which provides a combined estimate of the antenna section, the RF transceiver sections and the metallic and dielectric components incorporated in the mobile phone. Since the active measurement evaluates the overall performance of the mobile phone in terms of the TRP and TIS performance metrics, improvements to transmit and receive performance of the various sections can be implemented at different design stages. The performance evaluation of the antenna section in isolation is not truly achievable with the current measurement setup and protocols. This study [26], has demonstrated the use of a compact reverberation chamber for the evaluation of the OTA performance of the mobile phone with reduced measurement times. The OTA characterization can be performed in an anechoic chamber as well as in a compact reverberation chamber as described in figure 1.5-i.

Figure 1.5-i: OTA measurement facilities at CentraleSupelec using anechoic chamber (right) and compact reverberation chamber (left)

## 1.6 Overview of power control in GSM and UMTS

Power control is an important mechanism used to change the transmission power of the mobile phone (referred to as the mobile station (MS) in the case of GSM and referred to as user equipment (UE) in the case of UMTS) or base station (BTS) or both in the network for one or more of the following reasons, to reduce the system interference and improve the spectrum utilization, to prolong the battery life of the MS. When the received signal strength (RxLev) and the received signal quality (RxQual) are considered as good based on the specifications decided by the individual network operators, the transmission power of the MS can be reduced to a level sufficient to maintain the communication link without compromising the quality and this also lowers the interference to other cells. Information on the system requirements and link control implementation can be obtained in [27,28].

The power control can be used in uplink and downlink respectively. The uplink power control range MS is 30 dB, in GSM, considering the most widely used power class of MS (most MS belong to power class 4, which specifies the maximum transmission power is 33 dBm), the power reduction is always performed with a 2 dB step size. The downlink power control range is decided by equipment manufacturer of the BTS. Although whether to adopt uplink or downlink power control function is decided by network operators, all MS and BTS equipment’s must support this function.

To facilitate broadcast channel (BCCH) frequency pull-in and the measurement of the received signal strength (RxLev) (including the RxLev of neighbor cell BCCH frequency), GSM protocol specifies that no power control is allowed for the time slots in the downlink of BCCH.

The power control implemented in UMTS also serves the same purposes as described for GSM with one important distinction regarding the effect of the near-far problem. The near-far problem can be briefly explained as follows: consider two user equipment’s (UE) connected to a base station (Node B) such that one UE is close to Node B while the other is at the edge of the coverage provided by Node B. If both UE transmit at similar or comparable power levels, the power received from the nearer UE will be orders of magnitude higher than the farther UE. Since the signal of one UE is interference for the other UE, the farther UE will experience a higher interference and its signal level at Node B might be lower than the observed interference level. Unlike, GSM, UMTS uses WCDMA modulation scheme where the entire spectrum is available to the user. Unique spreading codes are used to spread the baseband data before transmission. The receiver then de-spreads the wanted signal, which is passed through a narrow band pass filter. The unwanted signals are not de-spread and will not be passed through the filter. Thus it becomes important that all the signals reach the receiver of the Node B with similar signal levels to enable efficient detection and avoid receiver saturation from a high signal level causing interference from an UE located close to the Node B. As a reference, a target desired signal to interference ratio (SIR) is employed and the power control is implemented to ensure the target SIR is reached for all the users [29]. More detailed information regarding the UMTS network can be obtained in [30]. To mitigate the various adverse effects, three main power control mechanisms are used in UMTS:

- **Open loop power control**: This power control algorithm is used in the initial stage of power control where the transmit level is coarsely set to a specific value when the UE is in the process of establishing connection with the Node B. The open loop power control tolerance is set at +/- 9 dB under normal conditions and +/- 12 dB under extreme conditions [21].

- **Outer loop power control**: This is a type of closed loop power control (CLPC) algorithm for attaining the desired Quality of Service (QoS) with minimum power utilization in order to reduce the interference [31,32]. The desired QoS and the SIR are largely interrelated as while establishing connectivity the target SIR is estimated for each UE in the uplink. The UE has to meet the transmit power requirements based on the target SIR which is periodically updated based on the uplink signal quality determined in terms of the block error rate (BLER). The downlink transmit power levels are optimized to meet the BLER required at the UE [30].

- **Inner loop power control**: This power control algorithm is often used in together with the outer loop power control. The capability of the UE to receive and respond to one or more power control commands in the downlink is an essential aspect of this power control algorithm. As a minimum requirement, the power is varied in steps of 1, 2 and 3 dB after the power control level is determined in order to achieve the SIR target. Each 10 ms UMTS frame is divided into 15 slots which can be used by the power control command giving a command update frequency of 1.5 kHz [21]. This response time is fast enough to mitigate the effects of multi-path fading.

## 1.7 SAROTA Concept

There is a general misconception that using a mobile phone with a lower reported SAR value necessarily decreases a user’s RF exposure due to the mobile phone, or in other words it may be assumed that it is somehow “always safer” using a mobile phone with a low SAR value than a mobile phone with a higher SAR value. While SAR value is an important metric in judging the maximum possible RF exposure from a particular mobile phone model, a single value SAR does not provide sufficient information about the amount of RF exposure under typical usage conditions to reliably compare individual mobile phone models. During typical usage conditions, the mobile phone transmit power is generally constantly varied during the course of communication.

It is worth noting that “all phones” cannot be reliably compared for their overall RF exposure on the basis of a single value SAR characterization. There might arise several situations where a lower SAR value may not correspond to a lower real-life exposure. The challenging aspects of the evaluation of real-life exposure are also closely linked to the measurement methodology and purpose of the SAR characterization. The single point SAR value is largely used to indicate conformance to the RF exposure compliance. This ambiguity that may arise in the assessment of the real-life exposure due to the dependence on the maximum specified SAR value has been recognized by the Federal Communications Commission (FCC). In the FCC "consumer guide", they have described some of the cases with the help of two mobile phones, one with a higher specified SAR value and one with a lower specified SAR value where the mobile phone with a higher SAR will lead to a lower RF exposure in a real-life scenario. Furthermore, some additional cases have been described based on the measurements performed for the purpose of this study. The above mentioned cases can be represented by a set of mobile phones referred to a device under test (DUT), where DUT1 always exhibits the highest SAR value, DUT2 exhibits a slightly lower SAR value and DUT3 exhibits the lowest SAR value.

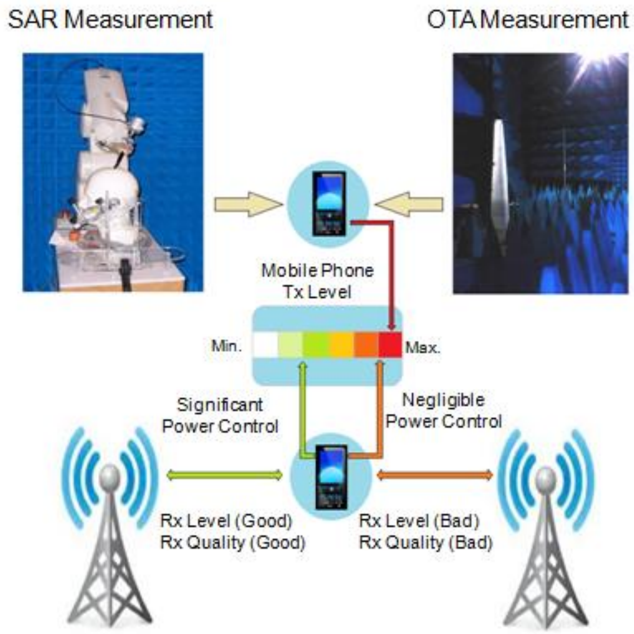


Figure 1.7-i: How SAROTA connects the laboratory based standardization with the real-life performance of the mobile phones.

The scenarios described below are only for real-life exposure where the DUT are operating under similar conditions.

- DUT1 might be assumed to exhibit a comparatively higher RF exposure compared to DUT2 based on their SAR characterization. However DUT1 might have a superior TRP performance than DUT2 such that will communicate at a lower power level than DUT2 as it experiences a higher degree of power control. In this case, DUT1 will, on average lead to a lower real-life exposure than DUT2.

- DUT2 might have a significantly superior TRP performance compared to DUT3. Due to the significant difference in the TRP, DUT2 has a higher chance of transmitting at a significantly lower power level. In such a scenario, the RF exposure due to DUT2 (which has a higher SAR) might be comparable or even lesser than that of DUT3.
- Consider DUT1 and DUT3, where DUT1 antenna design might lead to a situation such that for all the standardized measurement positions DUT1 reports a lower SAR value than DUT3 expect for one position where the SAR value is noticeably higher. As per the rules, the highest measured SAR value is allotted to DUT1. During typical usage conditions, on an average DUT1 will expose lesser than DUT3 depending on the usage pattern.
- Another important aspect is that the use of the hand phantom is presently not mandatory for characterizing the SAR performance of the mobile phones. However various ongoing studies are highlighting the effects of the hand sizes, hand grips, palm separation distance, etc. with respect to the location of the antenna (top, bottom or other locations) on both the OTA and the SAR values.

Keeping in view the above mentioned scenarios, the SAROTA index was introduced to account for both the SAR and OTA performance of the mobile phones [33]. The SAROTA index is simply expressed as the ratio between the peak 10g-SAR (SARmax) and the TRP (TRPmax) measured under laboratory condition for the same test configuration, i.e. same mobile phone position against the SAM head phantom, same traffic channel and same maximum transmit power level:

$$SAROTA = \left[\frac{SAR}{TRP}\right]_{same\ configuration} \qquad [\mathrm{kg}^{-1}] \qquad (2)$$

The SAROTA index provides a unique parameter to quantify the performance of a mobile phone in terms of both RF exposure and OTA performance. For example, it is predicted that a mobile phone with a high SAROTA index will lead to a relatively higher average real-life exposure than one with a low SAROTA index. It is also predicted that two mobile phones with the same peak 10g SAR values but different TRP values will yield different SAROTA indices and consequently different average real-life exposures. The average real life exposure (SARreal-life) can be derived from the SAROTA index as follows:

$$SAR_{real\text{-}life} = SAROTA \times TRP_{real\text{-}life} \qquad \text{[W/kg]} \qquad (3)$$

Where, TRP_real-life is the average TRP observed in real-life scenario with power control mechanism enforced by the base station. It is deduced from the instantaneous power emitted by the mobile phone (TxLev). TRPreal-life is then obtained from the power emitted by the mobile phone. TRPreal-life is averaged over the measurement period during which the mobile phone was connected to the network (typical measurement period used for this study are 10 minutes and 30 minutes). Here SARreal-life is related to the SAR measured for the head region.

Recently, LEXNET which is a European project [34], has introduced an Exposure Index to evaluate the global exposure experienced from a wireless communication network. This will take into account the mobile phone usage data, exposimetry data, location data, etc. to evaluate the population exposure and to optimize the network design and network topologies. In comparison, the goals of the SAROTA index are aimed towards providing a metric to compare individual mobile phones for their RF exposure under real-life scenarios and enabling the user to select the mobile phone which will lead to a lower RF exposure.

The SAROTA index can be used by the general public as well as the network operators to compare mobile phones to select the one with a lower RF exposure. As the mobile communication technology infrastructure transitions towards the next generation of technologies, a gradual phase out of the 2G infrastructure is likely be observed in many countries in the near future. As the data communication becomes more reliable such that the voice can be sent as data over the internet with similar quality of service as the conventional mobile communication (circuit switched), there is a likelihood of the majority of the voice communication being shifted to the voice over internet protocol (VoIP) either through Wi-Fi or the internet connectivity provided by the mobile network operator.

The SAROTA index can be effectively applied for these cases since the mobile terminal TRP performance is related to the efficiency of communication in the uplink to meet the target signal to interference ratio. A mobile phone with superior TRP performance is more likely to undergo the power control to satisfy the minimum requirements, lower the interference to other devices and optimize the battery usage.

# Chapter 2

# Characterization of measurement locations

In order to perform real-life exposure assessment with the mobile phones operating in typical usage scenarios, it is important to identify the capabilities and the limitations of the available tools and equipment's. The parameters of primary importance need to be identified in order to design basic measurements and experiments which are aimed at verifying the consistency of the observed data and various issues that can affect the measurements. Thus the shortcomings of the measurement setup can be addressed with an informed technical approach.

## 2.1 Software modified phones

To perform comprehensive RF exposure assessment, the availability of various network parameters is required. The access to these parameters can be gained through the cellular network provider or through accessing the measurement report (MR) generated in the mobile phone itself. The former approach requires a collaboration with the network providers which has its own logistical, technical and administrative limitations. The latter approach of accessing the MR required a mobile phone with an embedded software capable of recording various network parameters [58]. Currently, two classes of mobile phones exist, namely, feature phones which run on firmware and smartphones, which run on an operating system. The embedded software is typically a proprietary code custom built to be compatible with the hardware and the software of the mobile phone. Presently various applications (apps) are available on the Android and Apple iOS operating system platform for smartphones which are capable of monitoring the network parameters. However these generic apps are primarily designed to monitor the downlink received signal strength and quality along with parameters such as neighboring cells, traffic channel etc. What they generally lack is the most important parameter for performing an RF exposure assessment, is the uplink transmit level.

The information obtained from transmit and receive parameters is primarily used for analyzing drive test measurements on the wireless network and assessing the quality-of-service (QoS) and quality-of-experience (QoE). The measurements can be performed for both outdoor and indoor environments along with the real-time visualization of the information about the state of the various parameters under observation. The uplink and downlink air-interface parameters are can be logged on the memory card of the mobile phone itself. Some of the important parameters are listed below,

- Serving cell information – Cellular system, Channel number, Cell ID etc.
- GSM RF Parameters – MS power level, RX level (full/sub), RX quality (full/sub), DL DTX, Timing advance, FER, AMR parameters, Link quality estimate etc.
- GSM serving channel information – BSIC, Channel number, Hopping channels etc.
- Forcing Features: System lock (GSM, GSM900, GSM1800, and UMTS), Channel lock, etc.

It is evident from the brief description about the capabilities listed above; these phones can be utilized for various targeted measurements by using the forcing features. For example, the mobile phone can be configured to operate only on the GSM system and more specifically for GSM or DCS. Also the phone can be configured to lock on to a specific channel to analyze the performance on that channel in a given location.

All these features make the software modified phones suitable for being used for the intended purpose of assessing the real-life exposure due to mobile phones by analyzing how the mobile phones perform under typical usage situations and conditions. However, before proceeding towards commissioning these phones for performing measurements, it is important to study the parameters, at what intervals they are logged and exactly what is the nature of the information available for the parameters. As a first approximation, some specific parameters (MSP, RxLev, RxQual, Channel, etc.) are selected which are for the purpose of this study.

Various indoor and outdoor measurements were performed to assess the consistency of the data logs of the selected parameters. The compatibility of the raw data which is generally stored in a proprietary format which is later extracted using a proprietary tool to be transferred to a text document to be analyzed by standard tools is extensively tested. The base station emulator and a reverberation chamber was initially also used to test and verify the accuracy of the recorded data by the software modified phones.

## 2.2 Identification of the measurement parameters

In order to assess the performance of transmit and receive characteristics of the mobile phone whether under laboratory conditions or in real life usage conditions, certain parameters need to be identified based on the communication standard used. The measurements are performed for GSM (900 MHz) and DCS (1800 MHz) and UMTS (2100 MHz) bands in speech mode of operation. The mobile phones and base stations (BTS) must essentially transmit only that amount of power which maintains the communication link with acceptable level of speech quality and minimizing the co-channel and adjacent channel interference. Thus the transmitter section of the mobile phone needs to be capable of varying the power levels as instructed by the BTS while the receiver section of the mobile phone must have adequate sensitivity and selectivity to acquire and demodulate the received signal.

Since the focus of the study is on the RF exposure due to mobile phones, the power control mechanism mentioned for the measurements and experiments is the uplink power control (ULPC).

The transmitter performance is characterized for its in-channel operations and out-of-channel and out-of-band interference. The in-channel operations largely describe the link quality experienced by the user. The out-of-channel characterization describes the level of interference caused by a particular user towards other users within the same communication system. The out-of-band characterization describes the extent of interference caused by the user of one communication system towards the users of other communication systems.

The receiver performance is characterized for its sensitivity and selectivity. The sensitivity characterization describes the link quality experienced by the user under good, low and extremely low signal level conditions. Selectivity measurements determine the receivers' ability to process the desired modulated signals in the presence of strong signals in the adjacent channels. Alternate channel selectivity characterization describes the interfering signals are two RF channels away from the receivers' passband.

### 2.2.1 Mobile station power level

Mobile station power (MSP) level is the parameter that appears in the measurement report periodically sent by the mobile phone to the BTS. MSP describes the mobile phone transmit power level. For GSM and DCS the maximum and minimum power levels are defined power class IV and power class I respectively.

$$TX\_LEV_{GSM900} = 33 - 2x(MSP - 5) \tag{4}$$

$$TX\_LEV_{GSM1800} = 30 - 2x(MSP) \tag{5}$$

where, MSP value ranges from 5-19 for GSM and 0 – 15 for DCS bands respectively.

Thus the MSP value describes the transmit level (TxLev) in dBm of the mobile phone. The TxLev is a fundamental transmitter parameter which describes the possible range or distance at which communication is feasible. The GSM system generally uses dynamic power control in order to ensure that each communication link is maintained with the minimum amount of power possible which results in reducing the overall system interference and helps maximize the battery life of the mobile phones. By observing the instantaneous and the averaged TxLev over the duration of the communication gives an estimation of the RF exposure that will be experienced by the user.

### 2.2.2 Received Signal Level

As described in 3 GPP TS 145.008, RxLev is designated a value between 0 – 63, it describes the received signal level or the communication link signal level. The recommended RxLev at which the mobile phone is capable to sustain a good quality communication link is described in the table below,

Table 2-1: Reference sensitivity level for downlink power

| Band | Level (dBm) |
|---|---|
| GSM | -102 |
| DCS | -104 |

such that RxLev in dBm = -110 + n; n = 0 to 63

When RxLev = 0, it indicates that the received level is less than -110 dBm

RxLev = 0 < n < 63, indicates a received between -110+n dBm and -48+n dBm.

RxLev = 63, indicates that the received level is greater than -48 dBm

Using the information obtained from observing RxLev, the communication link environment can be categorized as good and bad in terms of the received signal level. When the RxLev is good, it indicates that the mobile phone initial nominal transmit power can be decreased up to a sufficient link received level and quality is maintained at the base station.

### 2.2.3 Received Signal Quality

RxQual is designated a value between 0 and 7, where each value corresponds to an estimated number of bit errors in a number of bursts. According to the GSM technical specification GSM 05.08, RxQual value reflects the equivalent bit-error rate (BER) before channel decoding summarized in the table below.

Table 2-2: BER to Receive quality conversion

| **RxQual** | **Bit Error Rate (BER)** |
|---|---|
| 0 | BER < 0.2 % |
| 1 | 0.2 % < BER < 0.4 % |
| 2 | 0.4 % < BER < 0.8 % |
| 3 | 0.8 % < BER < 1.6 % |
| 4 | 1.6 % < BER < 3.2 % |
| 5 | 3.2 % < BER < 6.4 % |
| 6 | 6.4 % < BER < 12.8 % |
| 7 | 12.8 % < BER |

The RxQual measurement is performed over all the received frames (104 TDMA frames) within a measurement period of 480 ms. The reported value is the average of the BER received over all the frames and is designated a value from one of the eight RxQual levels (0 through 7); where 0 signifies the lowest BER i.e. best performance and 7 signifies the worst case with a high BER. RxQual has two variants, RxQual_FULL and RxQual_SUB. When the measurement is performed over all the received frames, it is considered as RxQual_FULL. If some frames (out of the 104 frames) are not included in the measurement averaging process, the measurement is considered as RxQual_SUB. The mobile phone measurement report includes both the FULL and SUB values for RxQual.

The RxQual_SUB measurements are considered when the discontinuous transmission (DTX) mode is activated. The DTX is activated when no speech activity is detected. The DTX module present in both the mobile phone and the BTS contains a voice activity detector (VAD) which detects the presence of a continuously varying speech against a stationary background noise. The mobile phone and the BTS detect the DTX activity with the help of the silence descriptor (SID) frames. In cases, when the DTX is activated during the 480 ms measurement period as there is no speech activity, the SUB measurement will be averaged over only the SACCH and SID frames. However, the FULL measurement will be averaged over all the frames, out of which most frames (total frames – frames used for SACCH and SID) will be empty since no speech activity is present; hence, the FULL measurement will report a poor RxQual. It is therefore important to detect the activation of the DTX mode when the measurements are performed. In this study the RxQual_FULL values are considered and adequate steps are taken to ensure the DTX mode is not activated during the course of the measurement.

## 2.3 Preliminary investigation

The preliminary investigations undertaken after getting familiarized with the available tools and equipment's are described below. The initial measurements were designed such that the logistical and experimental procedural issues are identified. Based on this understanding the measurement protocols were developed and fine-tuned to account for the various issues that would subsequently be encountered. This was an incremental process with an aim to achieve the maximum optimization possible for the measurement protocols. The measurements were initiated in the indoor scenario in order to manage the logistics and the ease of adapting and improvising the measurement in event of some unexpected behavior on the part of the mobile phone. Each phase of the measurement was reliably standardized before commencing with the next phase of measurements.

## 2.4 SAR and OTA Characterization

A set of mobile phones of various form factors and models are used to perform various experiments. To perform a comprehensive analysis, the mobile phones are initially characterized for SAR and OTA for both GSM and DCS bands. The characterization is performed at the lower, middle and upper frequencies (reference frequencies) for the free space and the phone positioned in the right cheek configuration against the SAM phantom. The SAR characterization is performed using a standard dosimetry test facility while TRP characterization is performed using the compact reverberation chamber. The SAR and TRP characterizations are provided in the table below where both SAR and TRP characterization is performed at traffic channels (TCH) 975, 38, 124,

Table 2-3: 10g SAR (W/kg) characterization for the right cheek configuration

| **Phone** | **GSM** | | | **DCS** | | |
|---|---|---|---|---|---|---|
| | **975** | **38** | **124** | **512** | **700** | **884** |
| M1 | 0.163 | 0.222 | 0.155 | 0.078 | 0.056 | 0.064 |
| M2 | 0.299 | 0.292 | 0.299 | 0.132 | 0.135 | 0.130 |
| M3 | 0.633 | 0.692 | 0.685 | 0.376 | 0.397 | 0.437 |
| M4 | 0.525 | 0.573 | 0.406 | 0.245 | 0.254 | 0.200 |

Table 2-4: TRP (dBm) characterization for the right cheek configuration

| **Phone** | **GSM** | | | **DCS** | | |
|---|---|---|---|---|---|---|
| | **975** | **38** | **124** | **512** | **700** | **884** |
| M1 | 26.6 | 24.58 | 24.86 | 25.16 | 25.3 | 24.1 |
| M2 | 26.77 | 23.64 | 24.52 | 25.16 | 23 | 21.74 |
| M3 | 26.49 | 25.69 | 26.87 | 25.93 | 24.2 | 23.77 |
| M4 | 25.56 | 25.00 | 24.26 | 23.43 | 23.09 | 22.59 |

The above measurements are useful in designing the targeted experiments by considering both the SAR and the OTA characterization. If we consider the mobile phone M2 which exhibits lower SAR values for both GSM and DCS across all the reference frequencies when compared to M3 however the TRP performance of M2 is consistently observed to be approximately 2 dB lower at the traffic channel 124 when compared to M3. Identification of such differences is useful in designing the experiments [35]. The TRP measurements performed using a compact reverberation chamber have an uncertainty of +/- 1dB. The total uncertainty can be determined using [56].

## 2.5 Uplink Power Control Observations

The RF power control mechanism implemented by a network operator determines the transmit power level of the mobile phone and the transmit power level employed by the base station subsystem (BSS). The power control level to be implemented in each case will depend on the periodic measurement results reported by the mobile phone and the base station and the various cell and channel parameters. However, the exact power control strategy to be implemented will be determined by the network operator and it will usually vary from one network operator to another. The actual power control depends on several network parameters and it is difficult to determine the type of power control that will be implemented by the different network operators. Nonetheless, the location of the mobile phone with respect to the base station antenna and the associated received signal level (RxLev) and received quality (RxQual) along with the considerations of interference primarily determine the extent of power control that should be applied. The power control can be applied for both the downlink and the uplink but since we are herein interested in the real life exposure due to the mobile phone, only the uplink power control mechanism will be considered.

If the traffic channel (TCH) characteristics are such that both RxLev and RxQual are degraded then the mobile phone will tend to transmit at a higher power level (TxLev) and in extreme conditions the TxLev may be at the maximum power level i.e. similar to the laboratory conditions for the SAR and OTA measurements. On the other hand, if the channel conditions are such that both RxLev and RxQual are satisfactory then the TxLev of the mobile phone will be lowered till the communication may be sustained with an accepted level of speech quality. This also results in reduced interference towards the neighboring devices and optimization of the battery power consumption. Since the power control regulates the mobile phone TxLev, the analysis of the implemented power control can give an insight into the real life exposure experienced by the user. Indeed, knowing the characteristics of the power amplifier of the mobile phone –usually linear operation– and the TxLev, one can deduce the emitted power and the real-life SAR. Measurement and observation of the downlink and uplink RxLev and RxQual, inter-cell and intra-cell handover is required to estimate the communication link characteristic and investigate the possible reasons for the implementation of given power control.

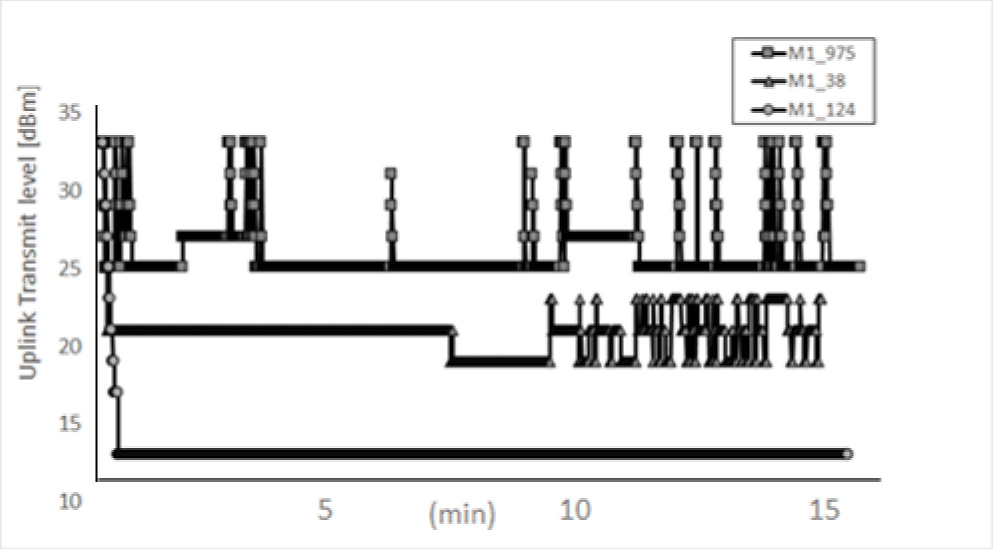


Figure 2.5-i: TxLev for the same network provider but on different traffic channels (TCH)

The uplink TxLev as well as the downlink RxLev and RxQual may be obtained using specific software modified mobile phones capable of monitoring the network parameters implemented during the course of the call. Herein, four identical models of software modified mobile phones used for the measurements. The TxLev patterns observed over a repeated set of measurements, display similar trends. The effect of TCH was extensively examined and with further repeated measurements and it was confirmed that the level of power control for the same network provider for a phone placed at a particular location may vary depending on the allotted TCH as described in figure 2.5-i. The TCH nearest to the lower, middle and upper frequencies were identified. This was done using three different SIM cards belonging to three different network operators. The observed power control levels at this location are different where the highest power control is recorded for the TCH with good received signal strength levels and least power control is recorded for the TCH with comparatively poor received signal strength levels. This can further be explained by the difference in distance between the measurement location and the location of the base stations belonging to three different network operators.

The stability of the transmit level for all phones when allotted the same TCH during their respective measurements is very peculiar. The measurement time for each phone is 15 minutes, the average TxLev is found to be stable and consistent as the variations in the received signal level and signal quality are in most cases found to be minimal during the entire duration of the measurement. If the received signal level and the signal quality remains steady then as expected the transmit level will also tend to be stable. Any minor instantaneous change if it does occur in the TxLev, will be averaged out.

## 2.6 Characterization of indoor environment for a real-life scenario

In order to perform various targeted measurements such that the uplink power control and the downlink receive signal strength and quality can be observed reliably, an indoor location was selected and characterized to perform the measurements [36] after application of the SAROTA index in real-life scenario was presented [37]. This indoor location exhibits satisfactory conditions for the received signal strength for the most of the network operators. Since the power control will be highly dependent on the network conditions, it is important to initially select the same network operator and as much as possible a relatively stable electromagnetic environment for all the real life measurements. Before commencing with the experiment, the received signal strength levels of the top two channels are observed. In event of a sustained change in the received signal level greater than 8 dB is observed for the channel used for the measurement, that measurement data is discarded. Based on the observations, measurements can be performed with the mobile phones operating on other network operators. To minimize the variations due to mobile phones, four samples of the same model are chosen referred to as (A1 to A4). The measurements are performed in the indoor environment for both the free space and the right/cheek configuration of the mobile phone positioned against the SAM phantom. The indoor environment is an empty room with its outer facing wall consisting almost entirely of glass windows. The phone and the phantom are placed on a wooden table located in-between the center of the room and the outer facing wall (Figure 2.6-i).

Figure 2.6-i: Measurement set up for characterization of the Indoor Environment

The mobile phones are configured to operate only on the GSM 900 MHz band with an audio uplink function which simulates a voice call by playing a recorded audio file to prevent the mobile phone from going into discontinuous transmission (DTX)-mode. The recorded audio file is played on repeat mode which helps simulating short and long call durations thereby eliminating the need for any separate audio device and other intrusions. Following a preliminary analysis of the RxLev, RxQual and TxLev measurement data where the call duration was varied in sets of 3, 5, 15 and 30 minutes over a period of several days at different times, it was observed that a duration of at least 30 minutes is required (for maintaining a conservative estimate of +/- 2 dB variation in RxLev) to reliably average out the effects due to unexpected instantaneous variations in the measured parameters. The rate at which each parameter of interest is recorded is approximately every 500 ms except for the mobile station power parameter is logged only when a change in power level is detected. The number of samples for each time duration is in the range of 10-15 samples. For each measurement it is ensured that the mobile phone battery is fully charged. All measurements are for the “speech mode” of operation.

The indoor environment is characterized for the selected channels available for a given network, N1, by measuring the corresponding transmit and receive parameters. It is observed that from the available traffic channels for N1 at this given location, there are four specific channels referred to as TCH-A, TCH-B, TCH-C and TCH-D that are allotted for majority of the calls initiated during the measurements. These channels have been characterized by configuring the mobile phones to operate at the selected channel during the entire duration of the call. Indeed not all attempts at forcing the channel lock were successful. Also there have been cases in which the mobile phone would not lock at the intended channel and instead automatically lock on to the nearest available channel. The TCH is always noted and accounted for while performing the analysis.

The network operators have been chosen such that their operating frequencies are in close proximity to the lower, middle and upper channels. The network operators are herein referred to as N1, N2 and N3 (not in specific order). The measurements have been performed in three sets such that for set I, the mobile phones are configured to operate on GSM using the system lock feature. The network operator allots the TCH for the live calls placed during the measurements. For set II, the mobile phones have been configured to operate on GSM and the traffic channel locked at TCH A. The measurements for sets I and II are performed for the same network operator N1 with A1 calling A2, and A3 calling A4. For set III, the mobile phones are locked at GSM for network operators N1, N2 and N3

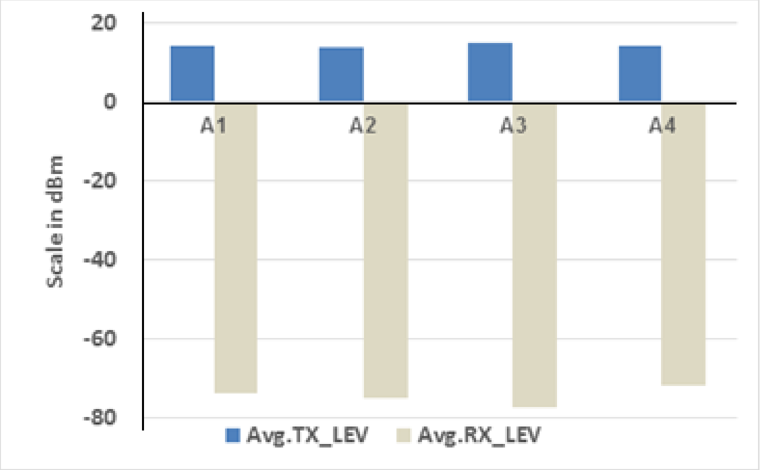


Figure 2.6-ii : Average uplink Transmit level and average downlink received level for the four phones locked to the same TCH

From figure 2.6-ii, it is observed that the TxLev measured for the four similar phones when operating on the same TCH is consistent within a variation of +/- 2dB. The observed RxLev is consistent within a variation of +/-4 dB. This implies that when the EM environment conditions are stable, the TxLev and RxLev parameters can be reliably measured.

Table 2-5: SARreal-life from average TRPreal life.

| **Network Operator** | **SARmax (W/kg)** | **TRPmax (dBm)** | **TRP real life (dBm)** | **Average RxQual** | **Average RxLev (dBm)** | **SAR real life (W/kg)** |
|---|---|---|---|---|---|---|
| **N1 at TCH A1** | 0.685 | 26.87 | 8.9 | 1 | -75 | 0.011 |
| **N2 at TCH A2** | 0.692 | 25.69 | 25.6 | 6 | -83 | 0.688 |
| **N3 at TCH A3** | 0.633 | 26.49 | 19.2 | 3 | -68 | 0.118 |

Table 2-5, provides the results for set III, where the effect of channel characteristics at the given indoor location for the three different network operators is examined. It also describes three different levels of power control observed with respect to the RxLev and RxQual characteristics for N1, N2 and N3. Maximum level of power control is observed for N1 with the combination where both the received signal level and the quality are satisfactory. For N2, it is observed that the effect of the power control mechanism is negligible since the RxQual is highly degraded indicating the presence of heavy interference in combination with the RxLev being worse than that for N1 and N3. It is obvious that for this case the mobile phone will transmit at a higher power level for a longer duration to avoid call failure. For N3, an intermediate level of power control is observed in spite of the RxLev being better than for N1 and N2 with a noticeable degradation in the RxQual. The difference in the level of power control implemented by each network operator is dependent on various factors that are yet to be comprehensively investigated.

## 2.7 Effect of Hand Phantom on the real-life performance of mobile phones

Figure 2.7-i: Setup used for comparing the effect of the hand phantom on the uplink transmit level.

The main objective of this study was to observe the effect of the hand on the transmit power level of a mobile phone in a real life scenario. In order to compare the effect, the experiment setup was designed to closely resemble a typical usage situation with the available resources [38]. A set of two samples of the same mobile phone model operating on GSM 900 MHz and DCS 1800 MHz frequency bands are used. The mobile phones are herein referred to as A1 and A2. The idea here was to compare the effect of the hand on the transmit and receive performance of the mobile phone relative to when the same mobile phone is used without the hand for the same position and configuration. This is achieved by positioning each mobile phone in the right cheek position against two separate SAM phantoms using a standard lossless positioner and a CTIA hand phantom, respectively (figure 2.7-i). Both A1 and A2 are software modified phones with embedded software capable of monitoring the network parameters. The mobile phones have been programmed to operate on the same network N with A1 calling A2. Both A1 and A2 have been configured to operate specifically either on the GSM 900 MHz band or the DCS 1800 MHz band. The call duration for each measurement was set to 30 minutes in order to effectively average out instantaneous variations and a recorded audio file stored in both A1 and A2 was uplinked when the call connectivity was established thereby ensuring the mobile phones do not switch to the discontinuous transmission (DTX) mode. All measurements were performed in the previously characterized empty indoor environment where the three walls of the room consist of concrete and one wall is essentially made of glass. Prior to the measurements, the indoor environment was characterized for N through repeated measurements of the various available traffic channels (TCH). One specific TCH each for GSM 900 MHz and DCS 180 MHz is then chosen for the measurements with the lossless phone holder and the hand phantom. The results obtained from repeated measurements describe below the effect on the hand phantom on the transmit properties of the mobile phones.

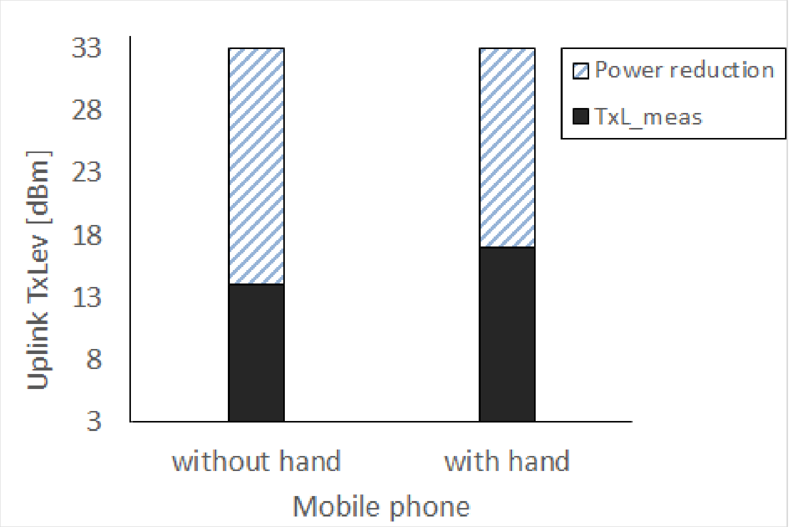


Figure 2.7-ii: Average uplink TxLev observed for the GSM band

From figure 2.7-ii, it is observed that the average TxLev at the given location with the hand is approximately 3dB higher than the TxLev without the hand phantom (i.e. using the lossless positioner) at 900 MHz. The measured average TxLev is 14dBm without the hand while with the hand phantom it is 17 dBm. This implies that the phone without hand experienced a higher degree of power control compared to phone with the hand phantom. The difference in power reduction is observed to be 3 dB. From figure 2.7-iii, it is observed that the effect of the hand phantom is more significant at 1800 MHz. The phone positioned using the hand phantom exhibits an average TxLev which is 8dB higher than when positioned without the hand phantom. This is in accordance with the studies reported by various other groups where it is observed that the effect of the hand phantom is noticeably higher at 1800 MHz than at 900 MHz. Similarly the effect of the hand phantom for the RxLev is described in figure 2.7-iv, where the RxLev degrades by nearly 10 dB for GSM and by nearly 15 dB for DCS.

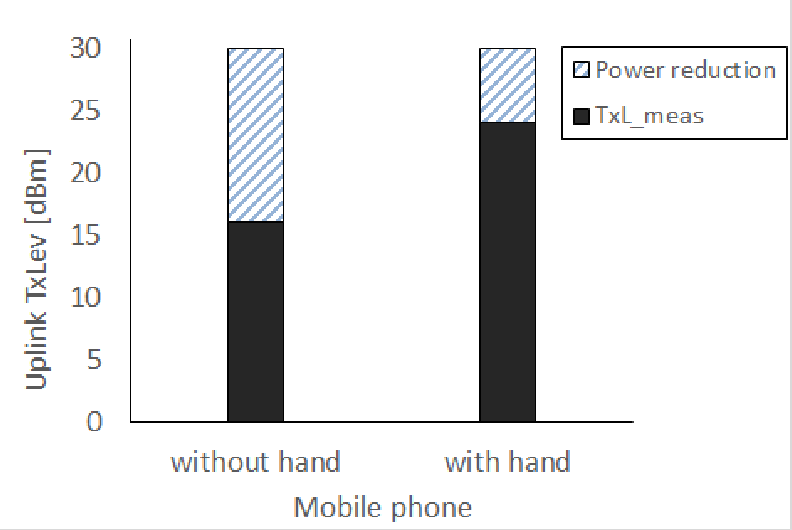


Figure 2.7-iii: Average uplink TxLev observed for the DCS band

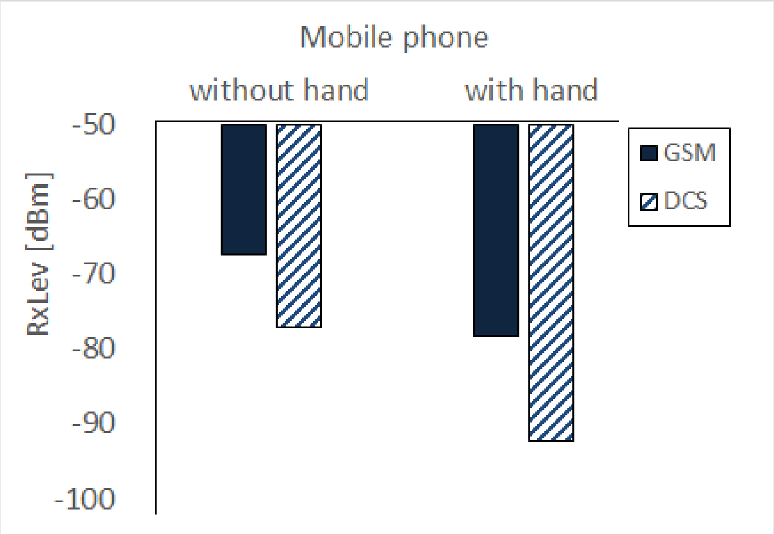


Figure 2.7-iv: The effect of hand phantom on the RxLev at GSM and DCS with bars on the LHS represent data measured without hand and on the RHS with the hand phantom respectively

Based on these observations the task of evaluating the real-life exposure was undertaken. The SAR and TRP characterization was performed for the same mobile phones with and without the hand phantom as described in figure 2.7-v and figure 2.7-vi respectively.

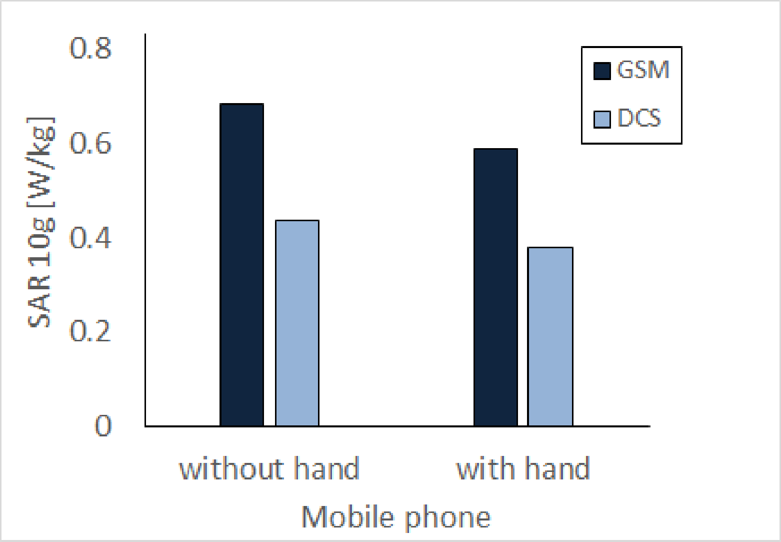


Figure 2.7-v: SARmax measured with the hand phantom and without the hand phantom for GSM and DCS

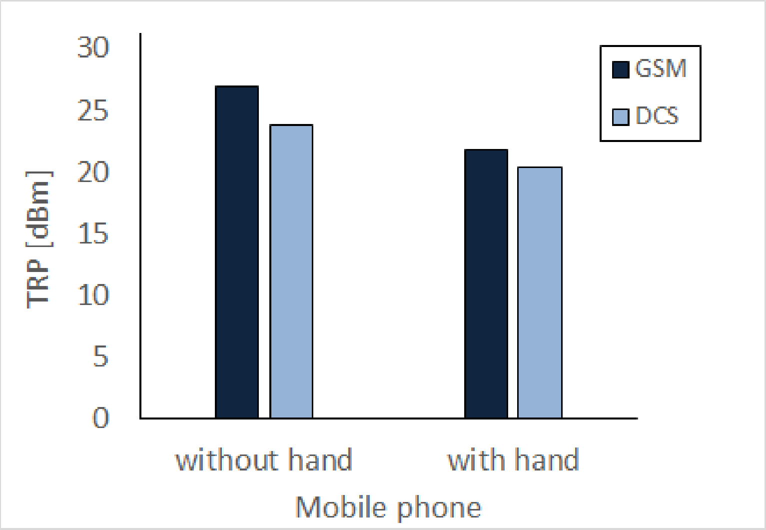


Figure 2.7-vi: TRPmax measured with the hand phantom and without the hand phantom for GSM and DCS

The following studies have previously investigated the effect of the hand on the SAR and or the OTA performance of the mobile phone [39-41]. With the presence of the hand phantom, the absorption of the power in the head region will be altered, the antenna performance is affected due to the effect of detuning and current distribution pattern inside the mobile phone will also be modified [40]. A reduction in SAR in the head is generally observed if the distance between the hand phantom and the mobile phone antenna is small as substantial amount of power may be absorbed in the hand [40]. An increase in SAR has been reported for certain distances between the palm and the antenna (15mm to 35 mm) at the higher frequency band [40]. Due to the absorption in the hand phantom and the detuning of the antenna also affects the TRP performance of the mobile phone.

It is observed that for this specific case, the SAR 10g value is lower when measured with the hand phantom. Also for the same configuration the TRP performance is degraded with the hand phantom compared to the TRP performance without the hand phantom. Thus there might arise an assumption that since the mobile phone with the hand phantom exhibits a lower SAR value, its real-life exposure should also be lower compared to that without the hand phantom. We test the validity of this assumption by performing the real-life scenario measurements.

From the SAR and the OTA measurements the SAROTA index was calculated (figure 2.7-vii). The SAROTA index predicts a relative increase in exposure when the mobile phone is used with the hand phantom compared to the exposure due to the phone without the hand phantom. This is attributed to the relative poor TRP performance due to the presence of the hand phantom.

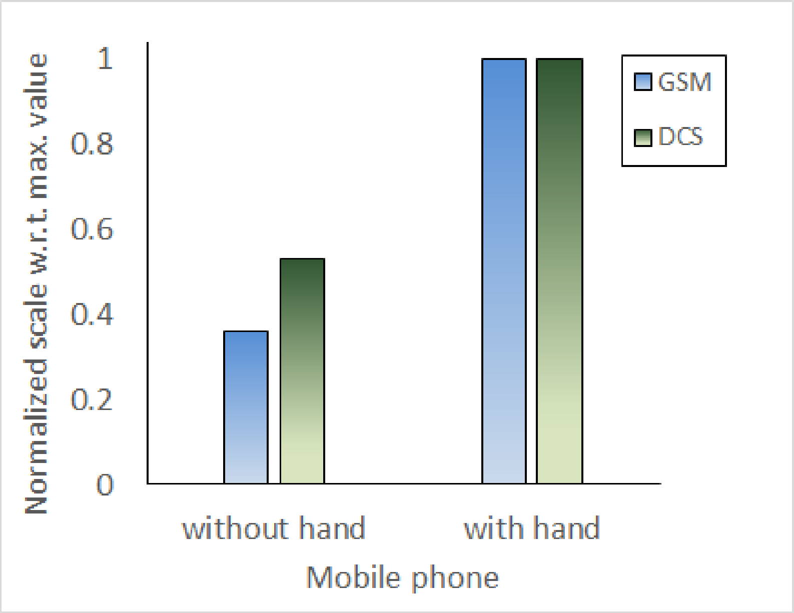


Figure 2.7-vii : The predicted SAROTA index at GSM 900 and GSM 1800

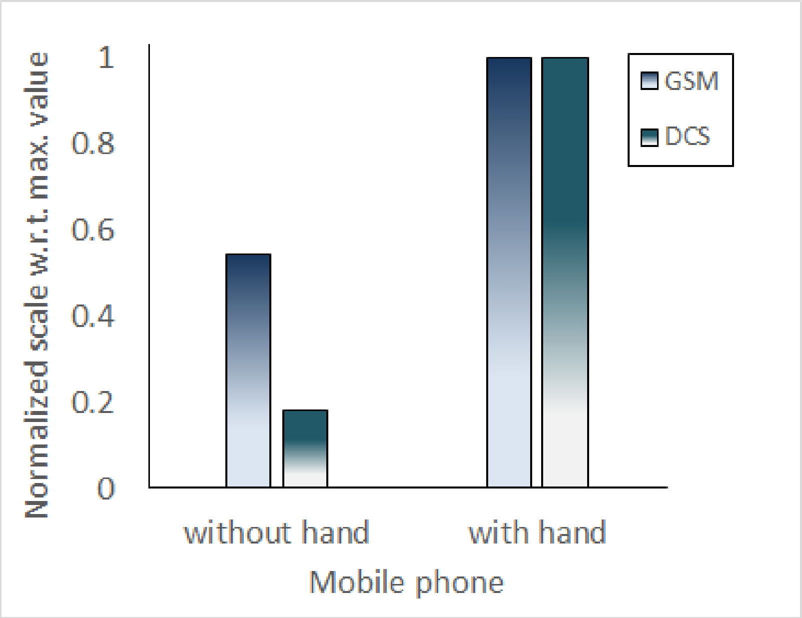


Figure 2.7-viii: The normalized real-life SAR comparison between the phone with the hand phantom and without the hand phantom.

From the average TxLev data obtained from the measurements, the real-life SAR is evaluated as described in figure 2.6-vii. Wherein the real-life exposure for the phone with the hand phantom is nearly 2 times higher than the phone without the hand phantom at GSM and for DCS it is nearly 5 times higher for the phone with the hand phantom. Thus the assumption that the phone with a lower SAR value exhibits a lower real-life exposure without considering the OTA performance of the phone can be false as shown by this specific measurement. Under similar conditions, a mobile phone with the hand phantom generally exhibits a higher real-life exposure (more than 2 times) compared to using the same phone without hand.

## 2.8 Outdoor Measurements: Stationary Scenario

The measurements described in this section are performed outdoor scenario where the measurement setup is confined to a fixed location (stationary). This measurement is undertaken as a follow up to the indoor stationary measurement scenario. The location selected is an open field with the institute building on one side while the rest of the sides are largely occupied with what can be described as a small forest region with a near absence of vehicular traffic and minimal human movement in its near vicinity. The received signal level at this location is expected to be stable when averaged over a sufficiently large period of time. Similar to the indoor measurements, various short duration measurements were conducted to assess the received signal stability and call connectivity at this location. The results were observed to be satisfactory for the initial phase of measurements.

Figure 2.8-i: Outdoor measurement setup for stationary scenario

The objective of these measurements is to analyze the variations observed in the received signal strength and received signal quality and also the power control implemented by the net-work operator. If the received signal strength and quality are found to be stable over a period of time, the pattern of reduction in the uplink transmit level of the mobile phones is expected to be consistent with what was observed for the indoor scenario. The mobile phones referred to as M1, M2 and M3 respectively. Also used is a set of 4 models of the same phone.

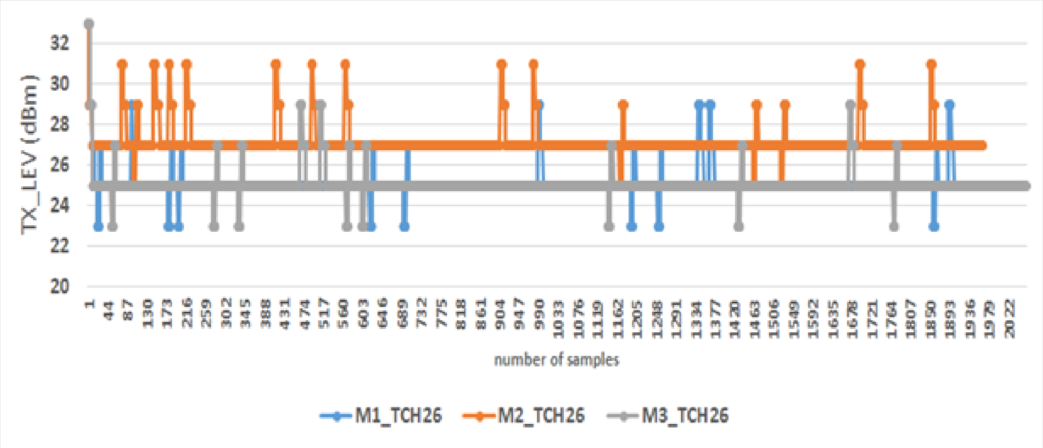


Figure 2.8-ii: TxLev comparison when the mobile phones are operating on the center of the GSM band

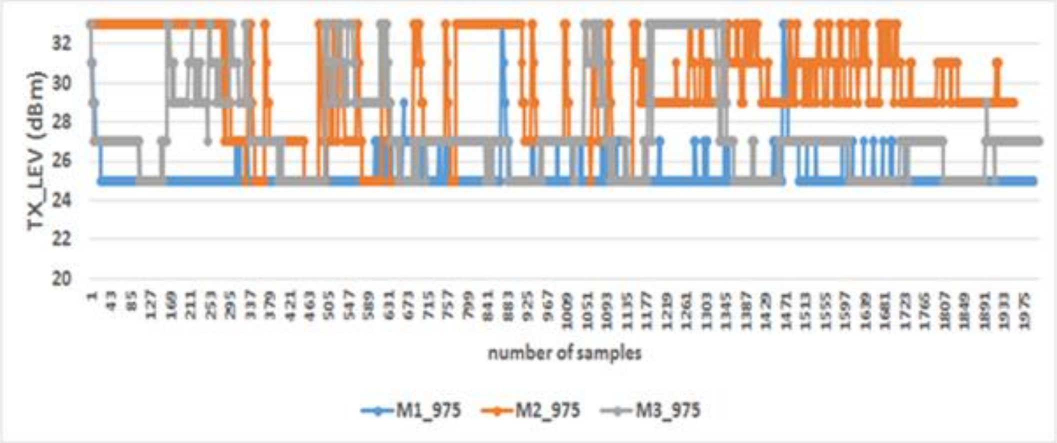


Figure 2.8-iii: TxLev comparison when the mobile phones are operating on the lower frequency of the GSM band

In the figure 2.8-ii, we observe that the average TxLev for M3 and M1 is found to be lower than that of M2 by 2dB. This is expected considering the TRP characterization of these mobile phones where the performance of M2 is relatively poor at the center of the GSM band. This observation is however not found to be consistent for the other measurements performed at the lower and upper TCH. Figure 2.8-iii describes the variation of the TxLev for the lower TCH.

A possible explanation is that the maximum difference in the TRP values of the three mobile phones used for this study is approximately 2dB, which is within the measurement error of the OTA characterization setup. In order to reliably demonstrate the expected effect of TRP on the implemented power control, the difference in the TRP for the mobile phones needs to be larger than the measurement uncertainty of the OTA characterization. Measurements similar to the indoor experiment to assess the effect of the hand phantom on the TRP and hence the implemented power control are undertaken for the outdoor scenario.

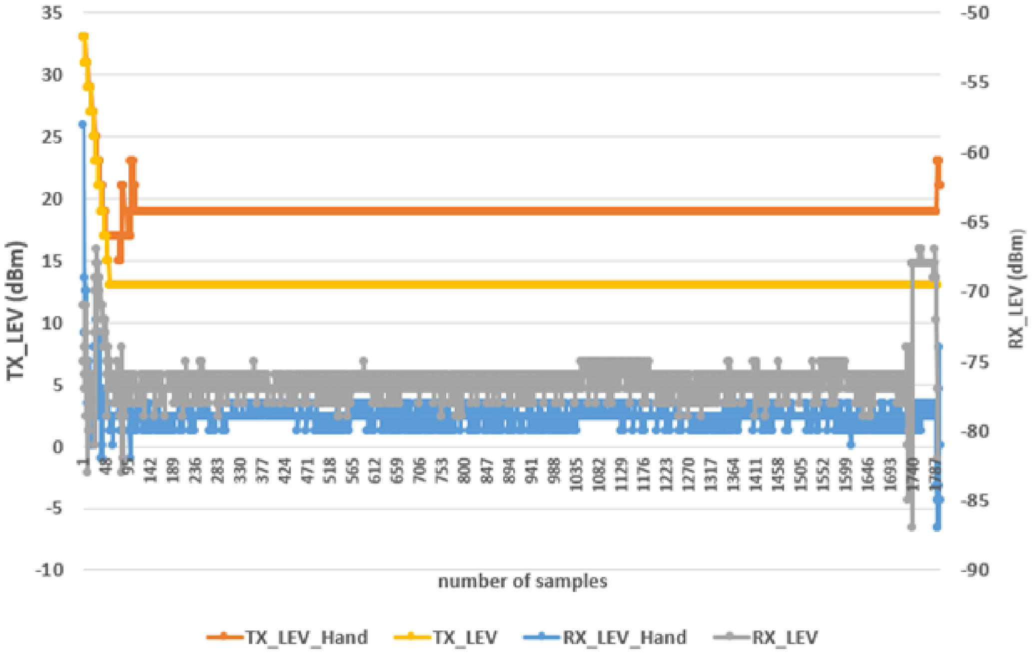


Figure 2.8-iv: TxLev and RxLev comparison for mobile phone with and without hand phantom operating on the GSM band

As observed in figure 2.8(iii), the effect of the hand on the implemented power control is clearly visible in the stationary outdoor scenario which is similar to that observed in the indoor scenario where the mobile phone without the hand phantom is experiencing a greater degree of power control (4dB on an average) while operating on the GSM band. The effect of the hand phantom is visible on both the TxLev and the RxLev parameters. The observed RxLev is found to be fairly stable for the outdoor scenario and does not exhibit any drastic variations except for when the call is connected and disconnected.

## 2.9 Outdoor Measurements: Mobility Scenario

The measurements were performed for the mobility scenario by undertaking a drive test where the SAM phantom heads were mounted on cardboard boxes to simulate a person in sitting position inside the automobile. A set of identical mobile phones is used for this experiment. One mobile phone is securely placed in the right cheek configuration by means of an elastic band while the other mobile phone is also placed in the hand phantom and positioned in the right cheek con-figuration. The hand phantom is secured with a fitting arrangement carefully designed for secure positioning considering the acceleration and the braking movements of the automobile.

Figure 2.9-i: Outdoor measurement setup for mobility scenario

A passive RxLev and TxLev field survey was conducted for a few days along certain selected routes to assess the network coverage for both GSM and DCS for the selected net-work operator. This was followed by trial and error measurements to assess and mitigate the situation in event of a call drop during the measurement and also accounting such events in the data logging process in order to perform the measurements.

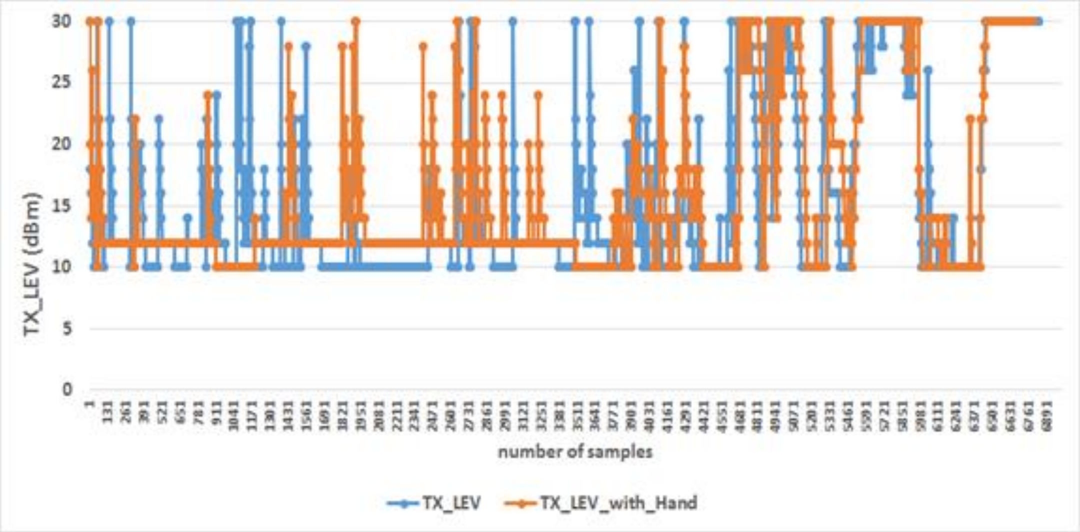


Figure 2.9-ii: Plot for TxLev comparison with one phone placed using elastic band and the other phone placed using the hand phantom

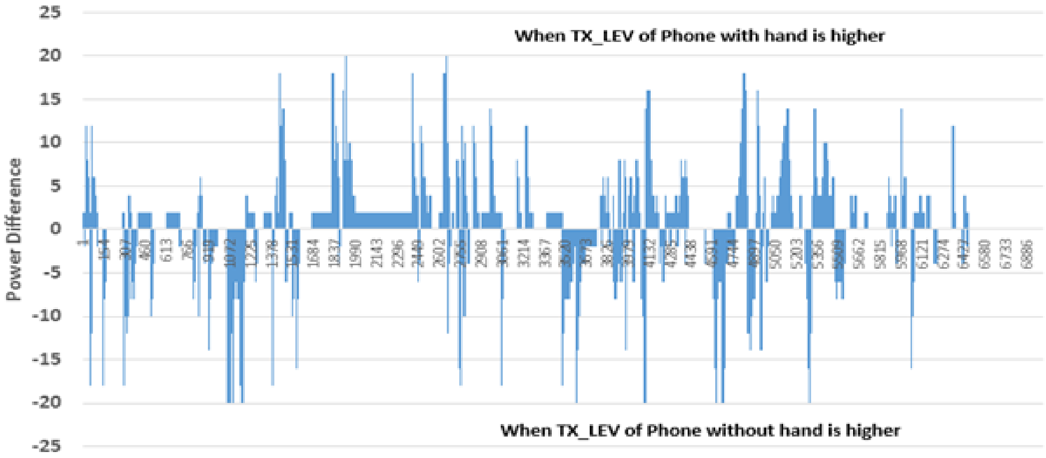


Figure 2.9-iii: Plot for TxLev difference with one phone placed using elastic band and the other phone placed using the hand phantom

From figures 2.9-ii and 2.9-iii, it is observed that the transmit levels of both the phones are comparable and the difference in the implemented power control is slightly visible however after averaging over the measurement time, the difference is less than 2 dB.

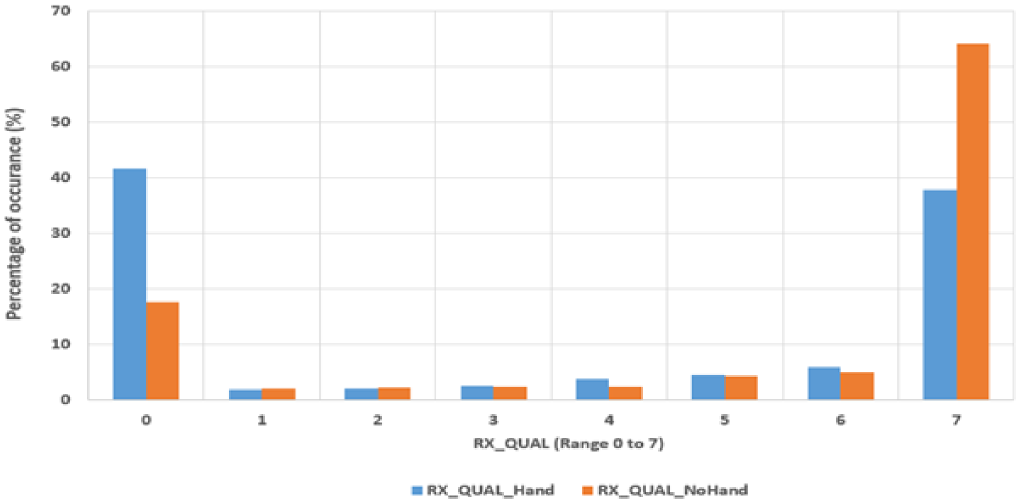


Figure 2.9-iv: RxQual comparison inside the automobile with one phone placed using elastic band and the other phone placed using the hand phantom

For this measurement it was observed that the received signal quality was undergoing frequent variations with the RxQual at 7 for nearly 40-60 percent of the call duration as presented in figure 2.9-iv.

The observations consistently indicate that for the mobility scenario (drive test) the implemented power control is directed towards maintaining the call connectivity in a rapidly changing received signal strength and or received signal quality indicating the allotment of a larger buffer margin to account for larger unexpected variations which may lead to a call drop.

In this scenario it is observed that the present setup is not reliable for performing a comparison between the two configurations (one mobile phone with the hand phantom and another without the hand phantom) since the surrounding space and proximity to various metal objects is not identical. This might lead to a situation where the uplink transmit power in unequally affected for one phone due to the surrounding environment and this would make it difficult to isolate the effect of the hand phantom. The measurement methodology followed relies on both the phones being on the same traffic channel to enable reliable comparison as the power control implemented is dependent on channel conditions. It could be possible to identify a region along the path where the TCH does not change. The movement of the vehicle beyond this region will lead to a channel change to sustain the communication. As it has been observed, more number of channel changes will typically lead to a higher average transmit level compared to operation on a single channel. This measurement is presently suitable for capturing the RxLev and TxLev performance observed for a particular network operator.

# Chapter 3

# Numerical characterization of mobile phones

Over the past few decades, the numerical and experimental techniques used for the determination of SAR distributions or induced electric fields and current densities in anatomically-based models of the human body have been continuously improved upon. Primarily driven by the advancements in the graphical processing units (GPU) such that a dedicated high performance GPU can be integrated in a desktop/server configuration, finer resolutions in terms of modeling the devices and anatomical structures are now possible. In this chapter, briefly, the important numerical techniques developed for bio-electromagnetic problems for the near-field exposures are highlighted. These techniques can be used to calculate currents induced in the human body by electromagnetic fields (EMFs) and for calculation of SAR used as a safety compliance testing metric for wireless devices and specifically mobile phones [1].

Among the various numerical techniques available today to solve for problems in electromagnetics, Finite-Difference Time-Domain (FDTD and Finite Integration Technique (FIT) are observed to be widely used in the industry standard commercial software packages available today.  For the purpose of this study, CST Microwave studio (MWS) is utilized for performing numerical investigation by modeling the phone in the CST CAD interface [55]. The phone is evaluated for the return loss, radiation pattern and SAR characterization. The time domain solver used herein in CST MWS is based on FIT which is a very versatile technique for design and simulation of RF and microwave components. FIT was introduced by Weiland in 1977 in the field of electrodynamics and since then it has been also used to solve problem in electromagnetics by transforming the Maxwell's equations into their integral form. A historical review of the use of FIT is presented in [42]. The geometry is discretized using a volume mesh (hexahedral mesh) such if the geometry has curved shapes, the meshing scheme can lead to a staircase approximation. Therefor to accurately model the non-rectangular geometry, it is essential to use a higher mesh resolution. The use of fine mesh in the initial stages of the design could be avoided in some cases by modeling the curved sections as closely resembling rectangular shapes. This is done to use less computing resources to speed up the simulation time. The initial model will be a coarse model which can be quickly optimized through multiple iterations in a relatively short period. This model serves as a first approximation to make initial estimates about the design parameters such as S11, gain and the radiation pattern. The FIT is capable of accurately handling the interfaces between different media which makes it usable for diverse applications with homogenous and non-homogenous media. Therefore the accurate modeling and numerical evaluation of an entire mobile phone positioned next to a SAM phantom containing a tissue equivalent liquid defined by relevant material parameters for the purpose of SAR investigation as per the requirement of this study is possible using FIT.

## 3.1 Antenna design and RF exposure

The influence of the human body (head and hand are generally in the reactive near field of the antenna) on the radiation properties of the mobile phone. In general, the proximity of the human body to the antenna degrades the antenna performance. Antenna characteristics that are mostly affected by the presence of the human body are radiation pattern, input impedance and radiation efficiency.

When a mobile phone transmits signals to communicate with the base station, part of the radiated power is absorbed by the human tissue. Usually, almost half of the radiated power is dissipated into the head region. At mobile phone frequencies, the body behaves as lossy dielectric material and absorbs RF power.

The type of antenna and the location of the antenna used in the mobile phone play an important role in determining the exposure levels to the user. Earlier models of mobile phones contained external antennas which were generally top mounted for a candybar or clamshell form factors. During the typical speech mode usage, the mobile phone antenna would maximally expose the ear region on the head depending on the current distribution. With the advent of the printed antennas, mainly the planar inverted F-antenna (PIFA) and its variants, mobile phones across various form factors have since adopted the integrated antenna module approach. Apart from the obvious advantage of compactness, the printed antennas could now be bottom mounted thus increasing their distance from the user typically exhibiting lower SAR values compared to the external antennas mentioned above. The printed antenna approach has also enabled the integration of antennas for Bluetooth, GPS, and Near-field communication (NFC) antennas inside the mobile phone chassis. This is particularly essential for achieving mobile phones with a uni-body design exhibiting a slim and compact form factor.

Taking the diverse usage patterns into account where the mobile phone is used with different hand grips along with the right/left cheek speech mode position; use of hands-free earphone/headphones where the phone might be held in the hand or placed in the trouser pocket of the user, the SAR limits are specified for the whole body exposure, different regions of the body, as well as the volume over which the average is made. The averaging test volumes—1g (U.S.) and 10g (E.U.) — are used in order to locate the region where the near field concentration of energy may be the highest. The compliance with the recommended maximum SAR limits is usually measured under the standardized conditions specified by the regulatory authorities. In some cases, the antenna is held at a minimum distance from the body in order to achieve SAR compliance. (The minimum distance is often mentioned in the user guide provided with the mobile phones and smartphones.)

As the form factors keep changing, so do the challenges faced by the mobile phone antenna designers in terms of achieving compliance for SAR and OTA performance. With the recent mass media awareness being generated about the potential effects due to mobile phone usage, there is further emphasis on mobile phones exhibiting lower SAR values. In [43], the effects of the PCB ground plane, mobile phone chassis, choice of antenna have been investigated. The SAR value and the SAR distribution are largely related to the fields induced by the antenna and the current distribution due to the surrounding metallic and dielectric components. From an antenna designer’s perspective, it is important to achieve a balance between the reduction in the SAR value and the increase in the OTA performance. This can lead to following situations, a) the mobile phone might be SAR compliant but not OTA compliant then an attempt to enhance the OTA performance might lead to a undesirable increase in the SAR value, b) the mobile phone is OTA compliant but not SAR compliant then an attempt to reduce the SAR value to achieve compliance adversely affects the OTA performance. This however generally depends on how the current distribution is affected. It is possible to tune the SAR and OTA performance such that a mobile phone with a reduced SAR and an enhanced OTA performance is realized. Since the most of the mobile phones sold in the market are required to operate on the 2G, 3G and 4G technologies, the antenna module is often composed of one or two multi-band antennas exhibiting resonances at the required frequency bands. Therefore, the antenna tuning is a rather challenging and complicated task as the SAR and OTA compliance is to be maintained for all the operating frequencies and bands and the tuning for one band should not adversely affect the performance and/or compliance of the other bands.

Considering the performance parameters for the mobile phone antenna during the design stage, the first parameter typically evaluated is the return loss values at the center frequencies of the operating bands and the impedance bandwidth achieved for each band. For a typical antenna, the return loss bandwidth is measured for the frequencies where the S11 = -10 dB condition is satisfied. This implies that 90% power is delivered to the input port of the antenna while 10% power is reflected towards the signal source. For mobile phone antennas, often a less stringent criteria may be adopted where the S11 = -6 dB is used as a reference. This implies that 75 % power is delivered to the input port of the antenna while 25% power is reflected towards the signal source. With the use of matching circuits realized either by distributed components of lumped components the impedance matching and impedance bandwidth can be further tuned.

The next aspect that is typically evaluated is the radiation pattern, gain and the radiation efficiency. The amount of power delivered to the antenna does guarantee that the antenna will be an efficient radiator. If the antenna is matched such that it exhibits large capacitive or inductive reactance, then sufficient amount of energy is stored around the near-field of the antenna which leads to reduced radiation efficiency. The surrounding metallic and dielectric components, such as the back cover, battery, and antenna support structure etc. can adversely affect the radiation efficiency and gain of the antenna. The fully integrated mobile phone antenna module is analyzed in the free space scenario to validate the performance parameters are satisfied. Before proceeding to the production stage, the fully integrated mobile phone antenna module performance is numerically evaluated in the presence of the SAM phantom. The effect on the impedance matching, radiation efficiency, and gain and radiation pattern is investigated. This followed by the SAR characterization for 1g or 10g average SAR and the peak spatial SAR for evaluate the SAR distribution. The effect of the hand phantom for the above parameters is also investigated to check for conformance to the compliance metrics. This analysis enables the designer to adopt certain performance tuning methods to change the current distribution to minimize the coupling and near-field emissions in a particular direction. A successful implementation of the tuning methods will achieve the goal of directing the least amount of energy towards the user and majority of the energy away from the user. From the empirical TRP measurements performed at the in-house test facility, it is observed that more than 50 % of the energy transmitted by the mobile phone is typically absorbed by the user head and hand region (e.g. at

GSM 900 MHz, TRP = 32 dBm for free space and TRP = 26 dBm for the right cheek position against the SAM phantom). Also the user hand has a detuning effect on the antenna impedance to a varying degree depending on the hand grip used. The detuning can lead to decrease in the TRP which can often lead to a slight decrease in the SAR value.

Since there is a greater emphasis on the SAR characterization of the mobile phones, it might not be unconceivable that to either achieve the SAR compliance or further lower the max. SAR value, the antenna location may be adjusted to position it further away from the head region of the user and/or the OTA performance (specifically the TRP performance) might be restricted such that it is compliant but not by a larger margin from the compliance threshold. The former, may or may not lead to a decrease in the TRP performance of the mobile phone. In the latter case, the TRP performance will be less than optimal but within the accepted levels of the compliance standards. This aspect is generally not known to the user that the mobile phone with a lower SAR value might have been realized at the expense of the TRP performance of the mobile phone and another mobile phone might display a slightly higher SAR value accompanied by a superior TRP performance which can affect the RF exposure experienced by the user during typical usage conditions.

## 3.2 Numerical Model

The information available in the freely available documentation indicates the phone consists of a bottom mounted antenna designed for tri-band operation at GSM 900 MHz, DCS 1800 MHz and UMTS 2100 MHz. The task of modeling the antenna and eventually the entire phone was undertaken by visually inspecting the actual phone model and the images of various modules of the mobile phone from the freely available documentation.

Figure 3.2-i: The actual antenna module (left) and the PCB (right) for reference

The antenna structure described in figure 3.2-ii, is first modeled with the mobile phone body approximated by a solid shape with material properties of a perfect electric conductor (PEC) ground plane. The feed point or the excitation to the antenna is modeled as discreet port connected to a microstrip line modeled over a FR-4 substrate. The antenna structure is connected to the microstrip line through a cylindrical pin. This structure is modeled such that the curved sections are approximated by linear structures to simplify the hexahedral mesh. Figure 3.2-ii also describes the return loss performance of the modeled antenna along with the ground plane. The S11 pattern clearly shows two resonances slightly exceeding 1 GHz and 2 GHz respectively which are close to the 900 MHz and 1800 MHz operating frequencies allotted for the GSM band. The lower frequency resonance has a S11 of -7 dB while the higher frequency resonance has a S11 of -16 dB. For mobile phones the S11 pass mark is typically at -6 dB which is less stringent compared to the matching requirement for the antennas in other applications. A S11 of -6 dB signifies 75% power from the source being delivered to the antenna and 25% power being reflected. However a good matching with 90 % or more power being delivered to the antenna is preferred. This implies the structure can be considered as the starting point for incorporating further details in geometry and improving the matching to achieve a better return loss at the lower frequency.

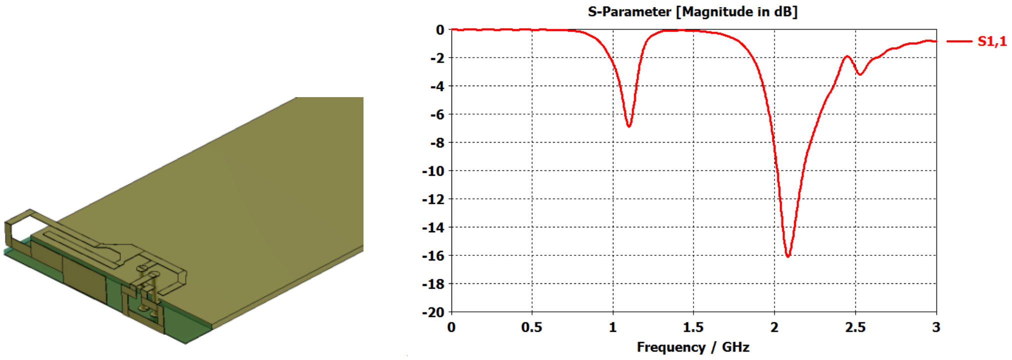


Figure 3.2-ii : Mobile phone antenna with the ground plane and the return loss

Figure 3.2-iii, describes the addition of the dielectric antenna support to the previous model. Due to the dielectric properties of the antenna support, the resonances are expected to shift towards the lower frequencies approximating which is indeed observed in the figure. The resonances are now closer to the GSM 900 MHz and GSM 1800 MHz frequency bands compared to the geometry without the dielectric support. Also the third resonance is more defined after the addition of the dielectric support structure compared to the previous model which is important as this can be used to extend the bandwidth of the resonance at the higher frequencies to better cover the UMTS frequency bands. This can be achieved by shifting the third resonance closer to the second resonance such that they sufficiently overlap to provide the bandwidth expansion.

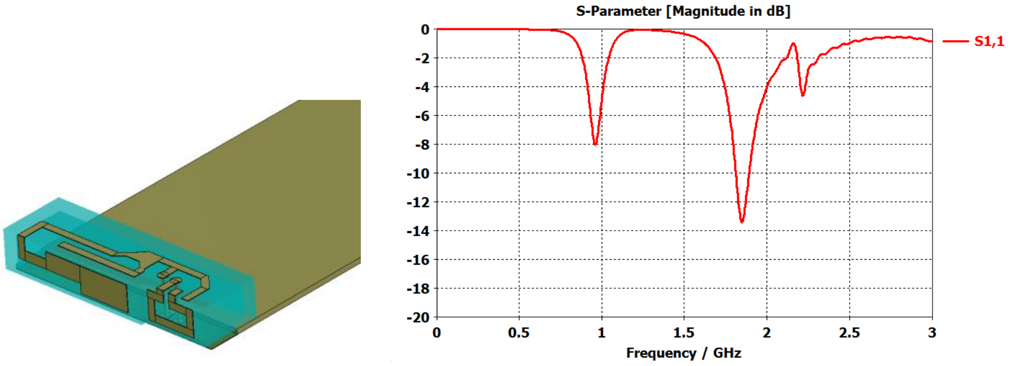


Figure 3.2-iii: Antenna along with the dielectric support structure and the return loss

The final mobile phone CAD model is generated by carefully examining the antenna geometry and the metallic components in the vicinity of the antenna. The numerical model of the phone consists of only the basic components which are sufficient to characterize the phone for its return loss and radiation pattern performance. The present status of the numerical model is the first approximation of the physical phone model. It should be noted that the production level detailed CAD geometry for this phone is currently not at our disposal. However, it is possible to perform numerical investigation on reconstructed CAD models modeled using the essential components [44-46]. The simulated return loss indicates the presence of resonances for the above mentioned bands of operation. The reconstructed mobile phone antenna model as well as the mobile phone component structure are described in figure 3.1-iv. Some components are expected to have negligible impact on the results and they are herein omitted to simplify the numerical model e.g. the camera which is located far from the antenna structure is not expected to highly influence the surface currents. Since the actual dielectric properties of the different components are unknown, a trial and error parametric investigation is undertaken to achieve the best match of the expected operating frequencies indicated by the manufacturer (the actual return loss of the mobile phone can only be measured by soldering a coaxial cable to the antenna feed which will be investigated in the near future once the currently on going mobile phone in-field measurements are concluded).

The return loss of the numerically reconstructed mobile phone is described in Figure 3.2-v. The return loss profile exhibits a sufficiently good match at the three frequencies: 900 MHz, 1800 MHz and 2100 MHz. This return loss performance is realized without the use of any matching elements. The S11 = -14 dB is observed at 900 MHz, S11 = -14 dB is observed at 1750 MHz and S11 = -8 dB is observed at 2100 MHz. This is further confirmed by examining the radiation pattern characteristics at 900 MHz and 1750 MHz with a free space gain of 2.25 dBi and 5.26 dBi respectively which closely correspond to the uplink center frequencies for the GSM MHz band and the DCS MHz band respectively.

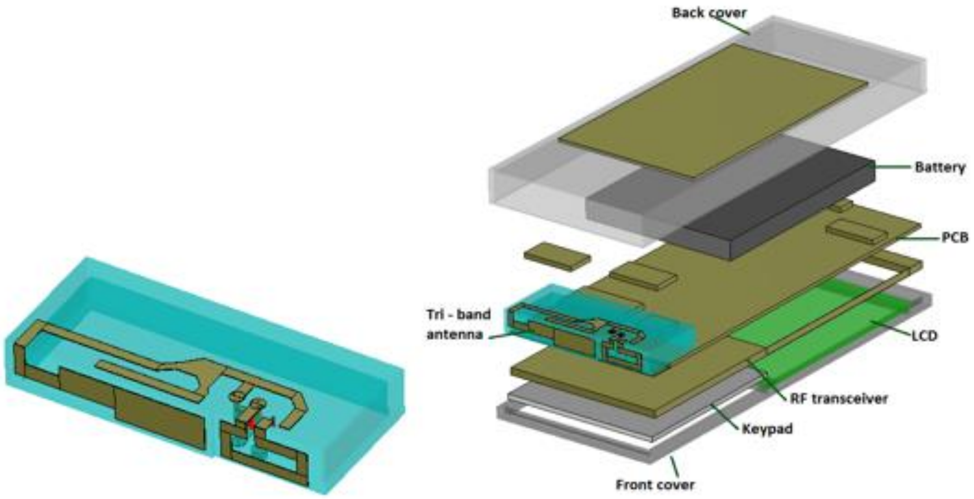


Figure 3.2-iv : Component view of the mobile phone CAD model and the zoomed-in view of the tri-band antenna.

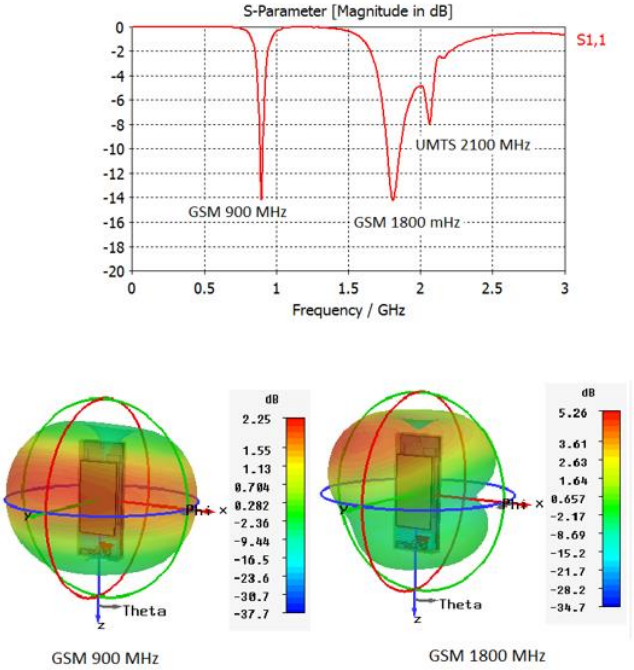


Figure 3.2-v : The S11 profile and the GSM radiation patterns for the mobile phone CAD model

## 3.3 Numerical analysis using SAM and hand phantom

The performance of the representative CAD model is further analyzed in the presence of the SAM phantom and the hand phantom. The mobile phone is positioned in the right cheek configuration against the SAM phantom. The mobile phone makes contact with the ear at a single point and also makes contact with the right cheek region at a single point. The mobile phone is aligned along the reference line positioned across the cheek on the SAM phantom. The hand phantom model used for this numerical analysis is the default model available in CST MWS. The mobile phone is placed in a fixed shaped hand grip of the hand phantom to represent as close as possible a real world hand grip holding a mobile phone as presented in figure 3.3-i.

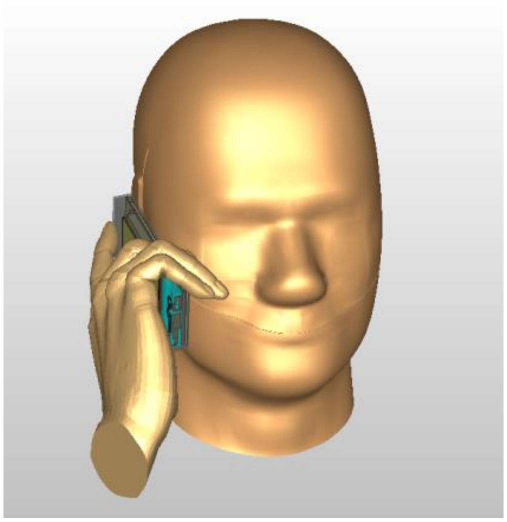


Figure 3.3-i: The numerical representation of the mobile phone placed in the right cheek position against the SAM phantom using a hand phantom

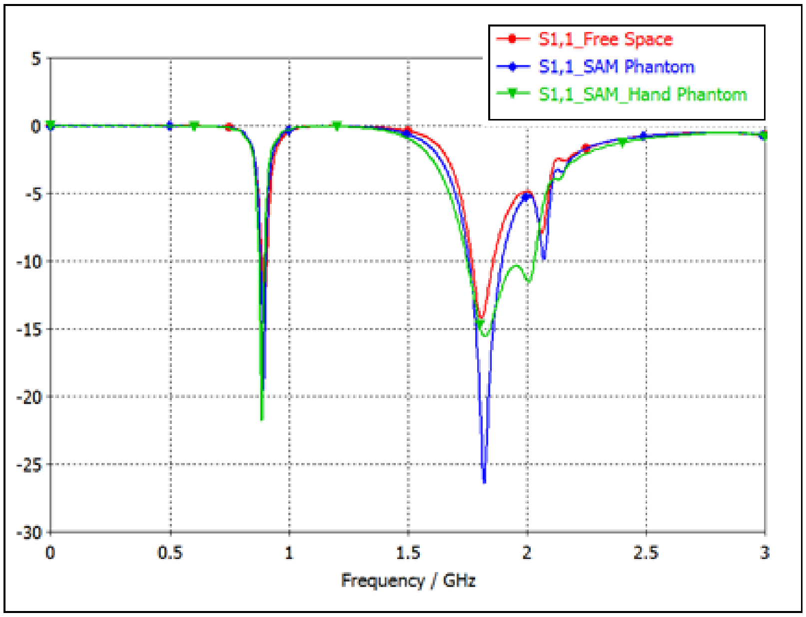


Figure 3.3-ii: Return loss comparison for the mobile phone in free space, phone plus SAM phantom and phone plus SAM and hand phantom.

The effect on the impedance matching represented by the return loss profile of the numerically modeled antenna placed in free space was presented in the previous section. In this section, the effect of the SAM phantom and the hand phantom on the impedance matching is analyzed. It is observed that at 900 MHz, the effect of the proximity of the SAM and hand phantom is of improvement in the matching as the S11 improves form -14 dB to -20 dB (SAM phantom) and to -22 dB (SAM + hand phantom) along with a slight shift in the frequency. At 1800 MHz, the effect is SAM phantom has a significant on the return loss. The S11 changes from -14 dB to -26 dB. The effect of the SAM and hand phantom is of increasing the return loss bandwidth from 1700 MHz to 2100 MHz.

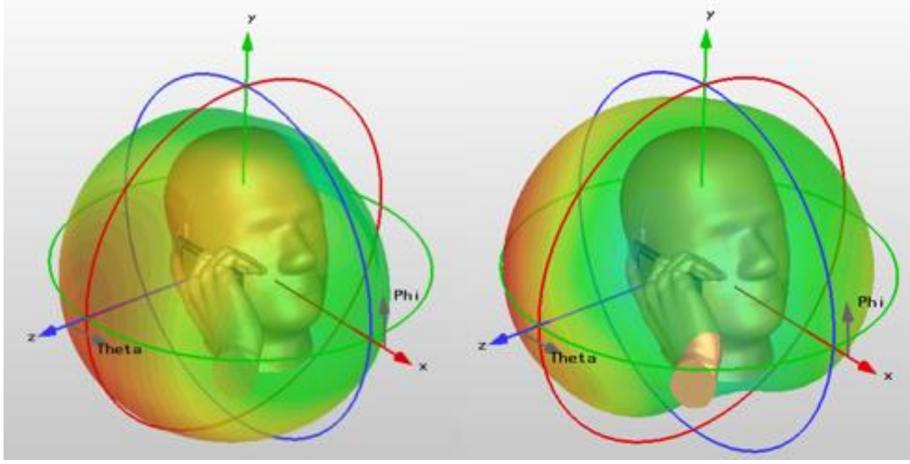


Figure 3.3-iii: The radiation pattern at 900 MHz (left) and at 1800 MHz (right)

## 3.4 SAR distribution comparison using flat phantom

Once the return loss performance was found to be acceptable for the free space configuration and the right cheek position against the SAM phantom, the CAD geometry was used for the SAR characterization at GSM and DCS bands. The peak spatial SAR distribution and the 10g average SAR were evaluated against the flat phantom. Simultaneously the actual phone was also characterized for its psSAR distribution and the 10g average SAR against the flat phantom at our SAR measurement facility. The numerical and the experimental results have been compared initially for the 10g average SAR, both the values were observed to be sufficiently close for a first approximation numerical model. The psSAR distribution (normalized with respect to the maximum value) is represented in figure 3.4-ii, the location of the region describing the maxima is found to be nearly identical. Similarly for the distribution at DCS, the location of the maxima is nearly in the similar region; however the secondary subsequent lower intensity distribution regions are not found to be similar. This can be explained by the rather simplistic nature of the numerical model compared to the structural complexity of the actual production level model. In the numerical model various components are excluded on purpose due to insufficient information about their dimensions and material properties and also to an extent to simplify the analysis for the initial phase of the investigation.

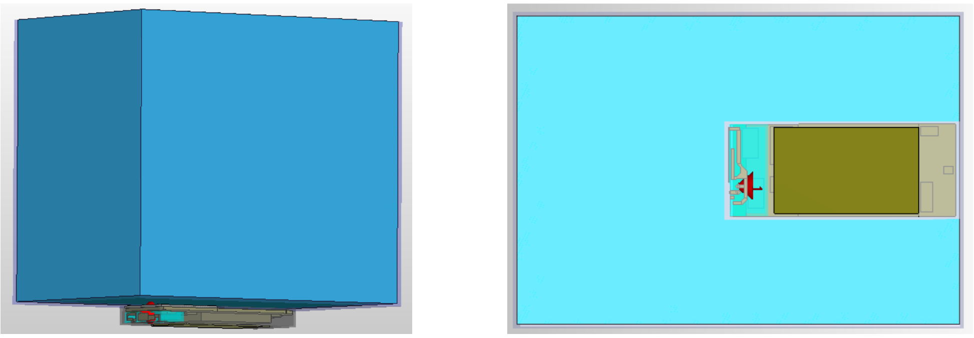
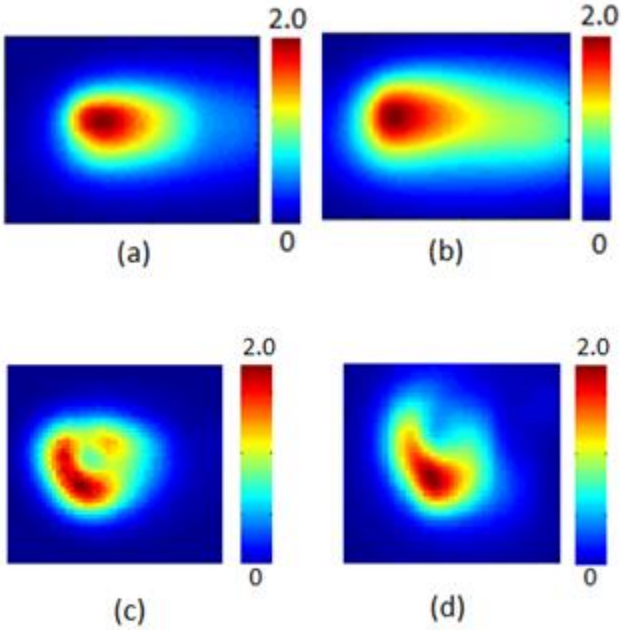


Figure 3.4-i: Numerical model of the flat phantom and the positioning of the phone



(a) (b) (c) (d)

Figure 3.4-ii: The point SAR distribution of the Ref phone at GSM and DCS where, (a) measured point SAR at GSM, (b) numerical point SAR at GSM, (c) measured point SAR at DCS, (d) numerical point SAR at DCS,

Since the SAM head model recommended by the SAR measurement standards, involves uncertainties which will add up to the uncertainties of the mobile phone CAD model, the test setup is simplified with the use of a flat phantom. In the numerical model, relative permittivity of 41.5, conductivity of 0.97 S/m and mass density of 1000 kg/m3 is assigned for the tissue equivalent liquid at 900 MHz. Similarly, relative permittivity of 40, conductivity of 1.4 S/m and mass density of 1000 kg/m3 is assigned at 1750 MHz. The model is discretized with 2.7 million hexahedral mesh cells (15 lines per wavelength, smallest mesh step of 0.05mm). The experimental validation of the numerical model was presented in [47] and has later been used to for calibrating a numerical CAD design with experimental data where the interpreted design and a commercial CAD model of another phone are used [48,49].

## 3.5 Designing external modification for the mobile antenna

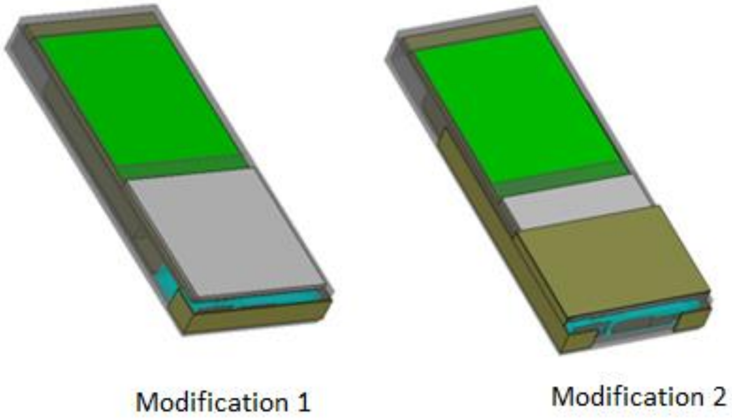


Figure 3.5-i: The CAD representation of DUT1 (left) and DUT2 (right)

The objective of this phase was to design external modifications in the near vicinity of the antenna such that the peak spatial SAR (psSAR) distribution of the modified phone will be significantly different form the unmodified phone. These modifications should also lead to a degradation of the TRP performance of the mobile phone.  Once the psSAR distribution and/or the SAR 10g value were observed to be significantly different, the modification was applied to the actual phone and this phone was then characterized for the SAR and TRP performance. The SAR characterization initially was restricted to the measurements using a flat phantom. Using a flat phantom was a logistically simpler and less error prone option from both the experimental and the numerical point of view compared to performing measurements with the SAM phantom. The positioning accuracy of the mobile phone and the flexibility available for the probe scanning is more practical to perform fast iterative measurements using a flat phantom. Also the computational time and resources required is less and the implementation of the hexahedral meshing is far simpler using a flat phantom.

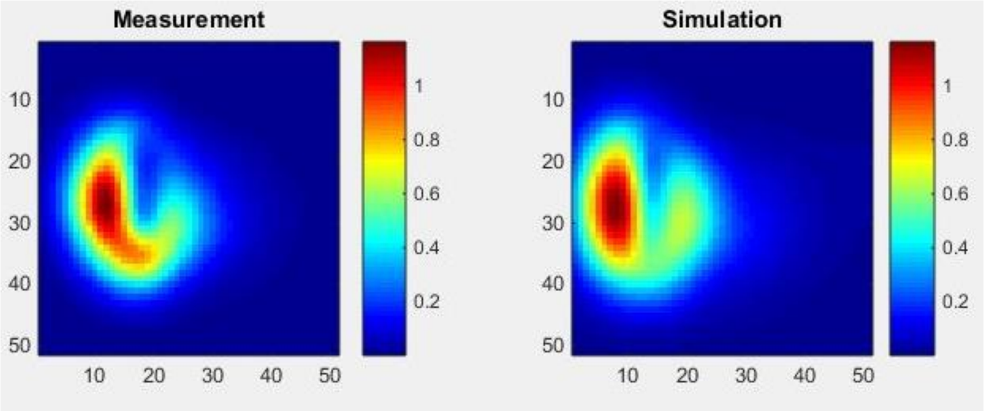


Figure 3.5-ii: psSAR distribution for DUT1 at DCS

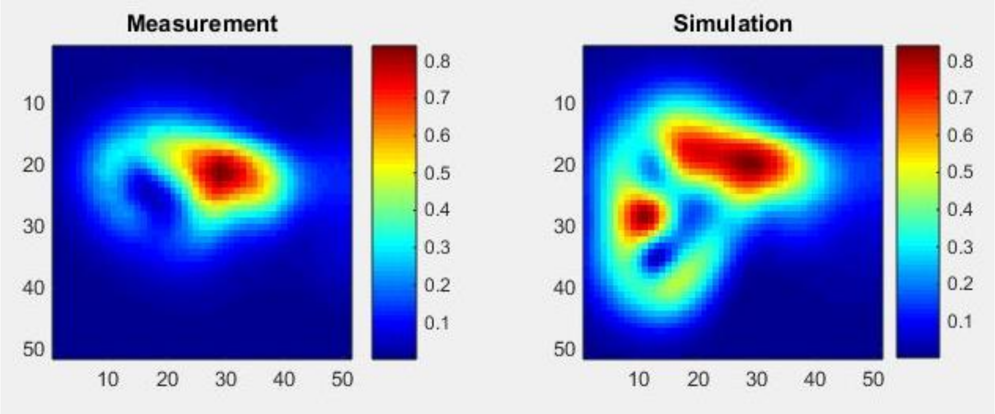


Figure 3.5-iii: psSAR distribution for DUT2 at DCS

### 3.5.1 SAR distribution comparison at DCS using SAM phantom

After analyzing the SAR distribution for the modified phones along with the flat phantom, the analysis of the SAR distribution against the SAM phantom with the phone placed in the right cheek position was undertaken.

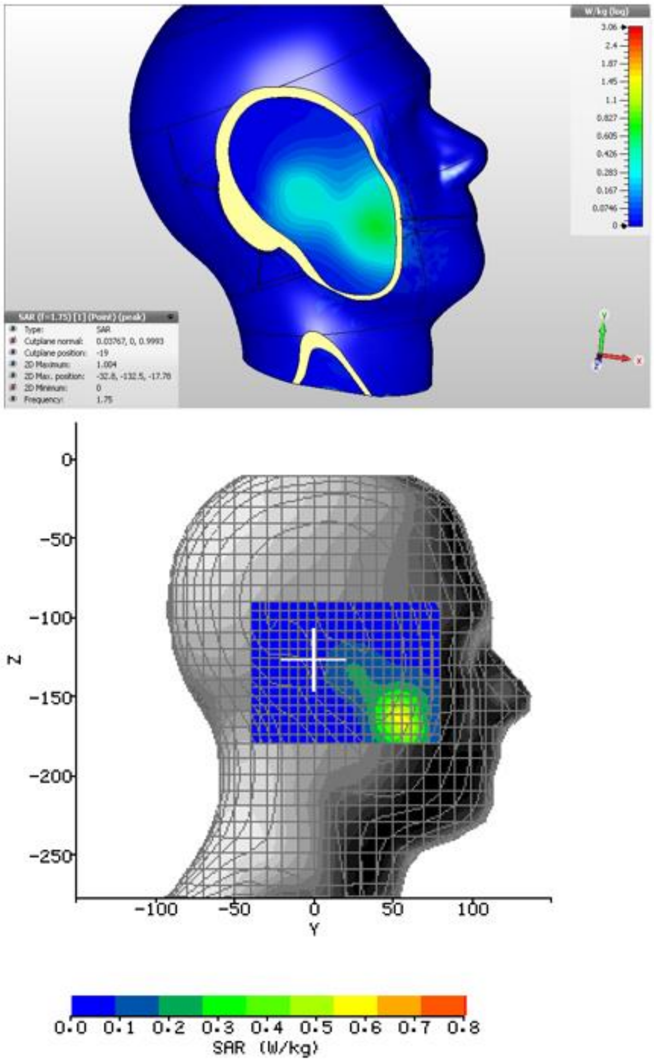

SAR (f=1.75) [1] (Point) (peak)
Type: SAR
Cutplane normal: 0.03767, 0, 0.9993
Cutplane position: -19
2D Maximum: 1.004
2D Max. position: -32.8, -132.5, -17.78
2D Minimum: 0
Frequency: 1.75

Figure 3.5-iv: SAR distribution simulation (top) and measurement (bottom) for REF

From figure 3.5-iv, it is observed that the contours of the SAR distribution exhibit a qualitative match for the numerical and experimental data for the REF phone.

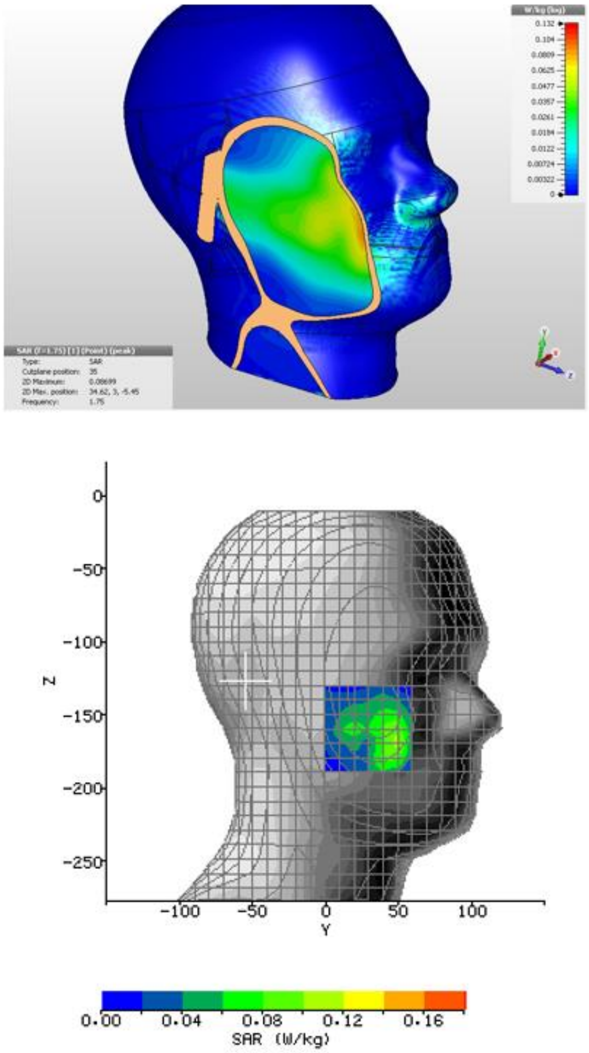


Figure 3.5-v: SAR distribution simulation (top) and measurement (bottom) for DUT1

From figure 3.5-v, it is observed that the contours of the near-maximum region of the SAR distribution are fairly similar for the numerical and experimental data for the REF phone. From the simulation data, it is observed that considerable energy is distributed around the eye, mouth and nose regions which was not observed for the REF phone.

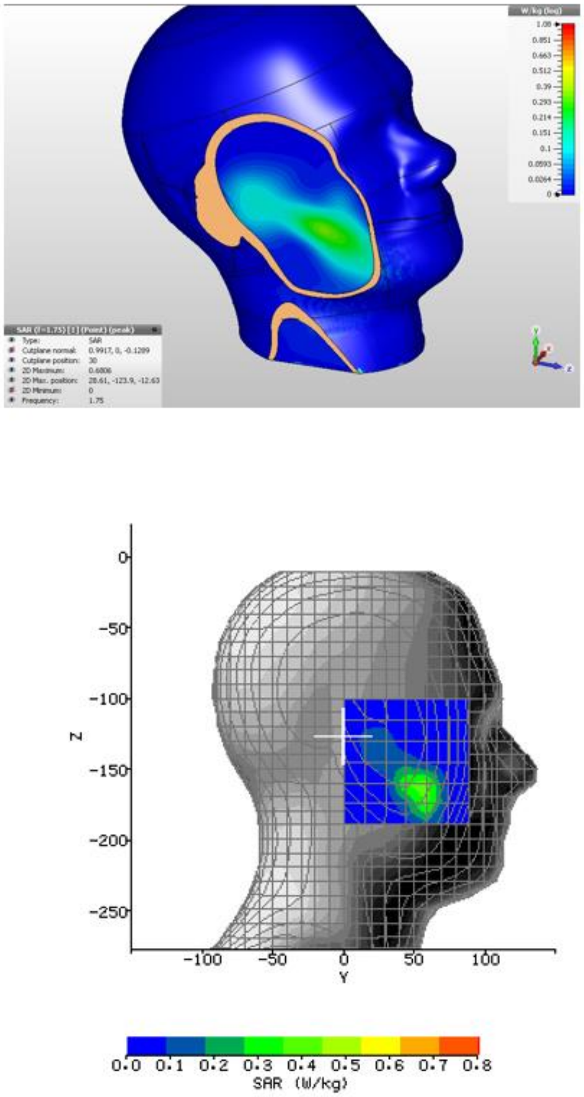


Figure 3.5-vi: SAR distribution simulation (top) and measurement (bottom) for DUT2

From figure 3.5-vi, it is observed that the contours of the SAR distribution are fairly similar for the numerical and experimental data for the REF phone where the elongation of the distribution on towards the ear can be spotted in the measurement visualization although it is rather faint.

From figures 3.5-iv to 3.5-vi, The RF energy is mostly concentrated in a localized region except for DUT1 (figure 3.5-v), where RF energy is observed to be additionally distribution at/near the eye, nose and mouth region. A possible explanation can be derived by observing the psSAR distribution measured for DUT1 against the flat phantom with respect to the psSAR distribution of REF. The maxima or the hot-spot for DUT1 is significantly shifted towards the left which signifies the distribution has shifted away from the phone which has a bottom mounted antenna. This could possibly lead to exposure of the eye, nose and the mouth region. This approach is extended to the comparison of REF and DUT2 and it is observed that the hot-spot is shifted towards the right which signifies a shift towards the screen of the phone. This should lead to a shift in distribution towards the ear region compared to the distribution observed for REF.

Table 3-1: SAR 10g at DCS

| **Device under test** | **Flat Phantom, SAR 10g [W/kg]** | | **SAM Phantom, SAR 10g [W/kg]** | |
|---|---|---|---|---|
| | **Measurement** | **Simulation** | **Measurement** | **Simulation** |
| REF | 1.75 | 0.93 | 0.41 | 0.472 |
| DUT1 | 1.163 | 0.539 | 0.079 | 0.059 |
| DUT2 | 0.841 | 0.425 | 0.34 | 0.315 |

Table 3-1, presents the comparison between the numerical and experimental values for the numerically modeled phones against the flat phantom and against the SAM phantom in the right check position. The simulation values for the SAR 10g with the flat phantom exhibit an underestimation compared to the measured SAR 10g values. However, the numerical and experimental values for SAR 10g with the SAM phantom exhibit a fairly good quantitative match.

# Chapter 4

# Experimental validation of the SAROTA index

The focus of this study is to address some of the important RF exposure concerns raised in the previous chapters. The experimental evaluation of the RF exposure can be aided by a metric which is capable of predicting the exposure in the presence of favorable network conditions. The proposed formulation is then experimentally validated to develop a methodology for the assessment of the real-life RF exposure and also validate the RF exposure profile predicted by the SAROTA index which can be used for the purpose of comparing mobile phones. The formulation for the SAROTA index (eq. 1) is developed further to better represent the values for the ease of comparison.

Considering the peak power for uplink transmission from the mobile phone is 21 dBm while that for GSM 900 MHz is 33 dBm, the values presented by the SAROTA index can differ with an order of magnitude. The formulation is developed to maintain the value within a similar range.

The maximum SAR value is normalized with respect to the SAR limit of 2W/kg according to the EU limits (using the U.S. limits is also valid) to obtain a ratio referred to as the SAR_factor,

$$SAR\_factor = \left[\frac{SAR\_max}{2\,W/kg}\right] \quad (6)$$

The maximum measured TRP value is normalized with respect to a reference TRP value which is typically the recommended TRP value for the communication system used.

$$TRP\_factor = \left[\frac{TRP\_max}{TRP\_ref}\right] \quad (7)$$

The SAROTA index is now obtained as the ratio of the SAR_factor and the TRP_factor,

$$SAROTA\_norm = \left[\frac{SAR\_factor}{TRP\_factor}\right]_{same\ configuration} \quad (8)$$

GSM case,

The TRP requirements from the 3GPP regulatory standard [50] are as follows,

Minimum TRP = 19 dBm;

Average TRP = 20 dBm;

Recommended TRP = 24 dBm;

The recommended TRP value is used as TRP_ref.

The TRP_max for a mobile phone at GSM will typically be observed in the range of 19 dBm to 27 dBm. Using these values, a range for the TRP_factor is obtained.

| | | | |
|---|---|---|---|
| TRP_factor | = | 0.3125 | for TRP_max = 19 dBm |
| | = | 1 | for TRP_ max = 24 dBm |

= 2 for TRP_ max = 27 dBm

Now, a generic SAROTA index can be established assuming typical SAR values for three phones. Lower SAROTA index implies lower RF exposure,

Table 4-1: Predicted SAROTA index for variable TRP

| | **SAR [W/kg]** | **SAR_factor** | **TRP [dBm]** | **TRP_factor** | **SAROTA index** |
|---|---|---|---|---|---|
| Phone I | 0.3 | 0.15 | 20<br>22<br>24<br>27 | 0.4<br>0.625<br>1<br>2 | 0.375<br>0.24<br>0.15<br>0.075 |
| Phone II | 0.5 | 0.25 | 20<br>22<br>24<br>27 | 0.4<br>0.625<br>1<br>2 | 0.625<br>0.4<br>0.25<br>0.125 |
| Phone III | 0.7 | 0.35 | 20<br>22<br>24<br>27 | 0.4<br>0.625<br>1<br>2 | 0.875<br>0.56<br>0.35<br>0.175 |

* TRP_ref = 24 dBm

Table 4-1, describes the RF exposure range a mobile phone can exhibit depending on its TRP performance. Considering a scenario where the Phone I has a maximum SAR value of 0.3 W/kg and a maximum TRP of 20 dBm compared with Phone III which has a maximum SAR value of 0.7 W/kg and a maximum TRP of 24 dBm. Phone III has a SAR value which is more than twice that of Phone I but Phone I exhibits a poor TRP performance. If both the phones are used in the same network such that the favorable conditions exist for the implementation of power control, Phone III has a higher probability of reducing its uplink transmit power level by a larger margin than Phone I for the TRP configuration mentioned above. In this case the SAROTA index predicts both the phones to exhibit similar real-life exposure. Under similar conditions, the same Phone III will exhibit a much lower real-life SAR compared to case where the Phone II has a maximum TRP performance of 20 dBm.

Examining the SAROTA ranges obtained for the three representative mobile phones above, the possible RF exposure profiles can be generated and the mobile phones can be compared for their performance under typical usage scenarios. In order to investigate the effect on the applied power control during live calls when the mobile phone antenna terminal performance is progressively degraded compared to a reference mobile phone. This follows from the previous phase of experimentation wherein it was observed that the implemented power control different for mobile phones with different TRP performance. This observation was made for the experiments for assessment of the effect of the hand phantom on the mobile phone. This presented a unique problem; the software modified mobile phones available at our disposal did not exhibit significant variation in the TRP performance to conclusively observe the effect on the implementation of the power control. The solution to this problem is described in the previous chapter where the external modifications were designed for the set of similar software modified phones.

Targeted experiments are performed with careful selection of DUTs along with the modifications to the DUTs and applied controls. The focus of this study is also aimed towards understanding the effects of the channel characteristics on the mobile phone terminal performance. The mobile phone terminal includes the effects of the antenna, power amplifier, RF circuits and the lossy dielectric components. The mobile phone terminal performance is an important factor used for determining the radio communication efficiency, effects on channel capacity and the calculation of the radio communication link budget. The proper evaluation of this parameter can enable the service provider to deploy more cost effective cellular network infrastructure. The reliable functioning of the communication link with satisfactory quality of service is one of the most important aspects for the mobile network providers.

However the antenna gain in its traditional form can lead to misleading calculations simply because of the way it is evaluated as it may not reflect the gain during typical usage scenario with various structures in the near proximity affecting the realized gain. To overcome this problem certain figures of merit (FOM) are utilized. These are the parameters of the OTA characterization, namely TRP and TIS. These parameters do not account for the link/channel characteristics. Some parameters which take into account the channel characteristic, viz. the mean effective gain (MEG) are also now being utilized [51-54]. However, currently it is not a mandatory parameter for OTA compliance. For this study, we use the standardized OTA FOM's for which we have a reliable measurement facility and also the SAR characterization is performed for the same configuration as that for the TRP which is very essential for predicting the SAROTA index. The communication link is characterized by the line-of-sight (LOS) and the non-line-of-sight (NLOS) components. A mobile communication system like the GSM, UMTS etc. in an urban area and specifically in the indoor areas, exhibits multipath channel properties without any dominant LOS component. The directional and polarization properties of the channel are important factors affecting the communication link performance.

During typical usage the user holds the mobile phone in a tilted position such that it is neither truly along the horizontal of the vertical orientation but at an angle nearly between the two orientations. So either of the two polarizations, viz. horizontal and vertical, will be received in the downlink with a signal strength determined by the propagation channel, directionality, polarization and the antenna efficiency. In order to assess the impact of the modifications, the measurements were first performed at GSM 900 MHz band, since the radiation pattern at this frequency closely resembles the pattern of an unequal length dipole due to the dominating effect of the ground plane on the pattern. At higher frequencies the radiation pattern is more directional and does not exhibit the horizontal plane symmetry as observed at 900 MHz. In order to negate the effect of the directionality of the antenna gain, the proof of concept measurements are performed first at the GSM 900 MHz band and later extended to the DCS and UMTS bands.

## 4.1 Selection of DUT

A set of identical mobile phones is selected for this study. The mobile phones are of the same model from the same manufacturer. The mobile phones with this configuration are so chosen to make reliable comparative measurements. All mobile phones were first characterized for their SAR and TRP performance. The observed variations in performance are within the measurement uncertainty margins of the SAR and TRP test setups.  Once this was validated, one of the mobile phones was chosen as the reference (will be referred to as REF) while the remaining phones to be referred to as DUT1 and DUT2 are externally modified to alter/degrade their TRP performance. The external modification is realized using near field impairment to the antenna terminal. This near field impairment is implemented using shapes cut out from a copper tape (thickness of *100 microns) to represent the modifications performed using the numerical simulations. The modified DUT's are again characterized for their SAR and TRP performance.

It is observed that the REF exhibits a higher SAR value compared to the DUT's however it also has a better TRP performance compared to the DUT's. This implies that the modifications have lowered the SAR values in the DUT's as well as the TRP performance has been lowered (exception at UMTS). According to the general perception, the phones with lower SAR values should exhibit a lower real-life exposure. This assumption is not necessarily true specifically when the TRP performance of the phones is comparatively poor compared to a phone with superior TRP performance with a relatively higher SAR value. Performing measurements to validate the assumptions by combining the effect of the network strategy adopted/implemented by the network provider is challenging since the network strategy is an unknown variable for this study. The strategy is largely based on the guidelines specified by the European Telecommunications Standard institute

(ETSI) however the network providers are allotted the freedom to modify and adapt according to their requirements for quality of service within the framework of the specified standard.

It was decided to proceed with certain basic and simplified assumption which are described as follows,

The phone with the best TRP performance will experience a higher degree of power control compared to the phones with comparatively poor TRP performance. This is based on the concept that the phone with the best TRP performance has a larger margin available for reduction of transmit power (TxLev). In simple words, the phones with poor TRP performance will transmit at a relatively higher power level. This assumption is tested for the good, satisfactory/less than satisfactory and bad network condition.

The network condition is classified according to the received signal strength and the received signal quality. When received signal strength is between -52 dBm to -70 dBm and the received signal quality is 0-3 (0 being best and 7 being worst) it is classified as good network condition. Similarly for a condition of RxLev between -70 dBm and -85 dBm and RxQual between 0-3 is classified as an intermediate network condition. However the RxQual might suffer due to interference even if the RxLev is worse than -85 dBm. In this case the challenge posed by the lack of information of the network strategy is greater since the increase in the TxLev in a high interference network situation is counterproductive to the overall system stability. However if the total network stability is not threatened then an increase in TxLev could be observed. For RxLev worse than -85 dBm and RxQual in the range of 4-7 is considered as a bad network condition and it is expected that in this condition, the mobile phone will generally experience the least amount of power control. The network condition status is classified with respect to the REF phone. All references to power control in this phase of the study are for the uplink transmit level.

It has been observed that in the two extremes of the network conditions when it is good and bad respectively, there is a high possibility of the power control level getting saturated and for the worst case, it being non-existent. For a condition of good and very good RxLev and RxQual, the power control level implemented will be optimized up to the safety/buffer margin decided by the network operator to guard against connectivity failure that may arise due to instantaneous variations. Assuming a buffer margin of 10dB at the GSM MHz frequency band implies that of the 30 dB power reduction margin, only 20 dB is used, i.e. for this case, the lowest transmit power level requested from the mobile phone is observed to be 33dBm - 20dB = 13dBm. Thus in the good network condition, all the test phones are able to satisfactorily connect with the base station with the least amount of transmit power level (i.e. 13dBm). In this case the difference in the TRP between the REF and the DUT's is not significant enough to observe the effect of the advantages of the higher TRP performance. The DUT's with poorer TRP performance are able to transmit at the lowest power level dictated by the base station since the receiver sensitivity at the base station has enough margin to essentially mitigate the poor TRP performance of the modified DUT's.

Figure 4.1-i: From L-R, REF, DUT1 and DUT2

## 4.2 Selection of Controls

As stated in previous chapter, the DUT used are software modified phones such that the embedded software makes it possible to select/force the phones to operate with certain selective features and modes of operation. Coupled with the controls possible with the DUT used, indoor locations are identified to perform the measurements where the required network conditions are observed. One network operator is selected and the indoor locations for the network conditions described as good, satisfactory, bad and worse are identified. The measurement time is optimized based on acquiring at least 1000 data points for each parameter to perform the averaging. The data is recorded every 540 ms, this implies a measurement time of 10 minutes provides more than 1000 data points. The changes in network condition over the 10 minute period are averaged over batches of 10 measurements performed per phone at each location.

## 4.3 Measurements and results

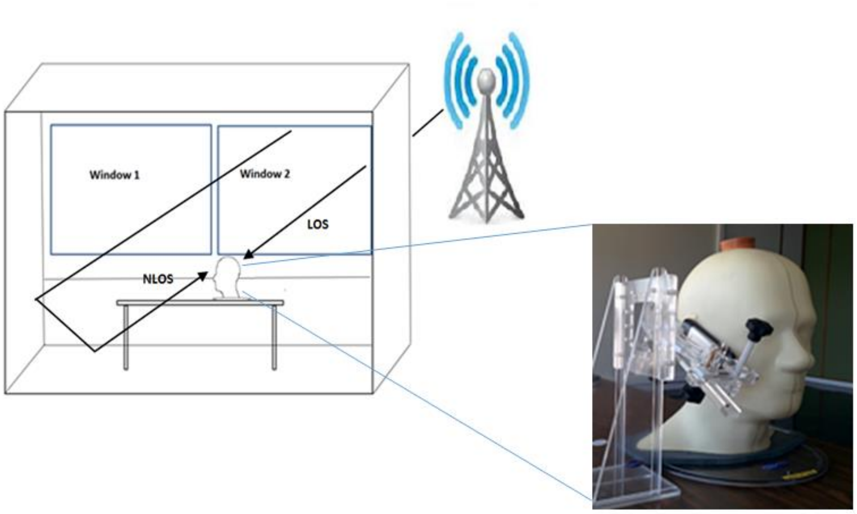


Figure 4.3-i: Representation of the characterized indoor environment used for the measurements

The measurements were initially performed for the GSM 900 MHz band in the indoor environment which was characterized previously. At this location the network conditions status is classified as good network condition. For this round of measurements, all the phones experienced the maximum level of power control despite having differences in TRP performance. For the GSM 900 MHz band, this location is not optimal to observe the effects of the difference in the TRP performance. For a multi-band mobile phone, the SAR is generally observed to be highest at GSM 900 MHz, hence the maximum real life exposure from the phone will also be highest at this band (for comparable network conditions) which makes it important to investigate the effects at this band. After a few iterations of additional surveys, an indoor location was identified with network condition status as intermediate. This room is located on the same floor separated by a distance of less than 20m, it is similar in size to the previously characterized empty room except that this room is not empty. The presence of metallic objects and structures in the form of computers, test and measuring instruments, cupboards and shelves create a different RF environment compared to the empty room as is evident from the consistently observed difference in the received signal levels. Further experiments were initiated to identify the best channel (i.e. best RxLev and RxQual) and to test if the channel lock feature does not lead to a call drop before the 10 minute measurement period. It was observed that the channel lock feature works for an average of 8 out of 10 measurements at this location, which is good enough to initiate the batch measurements. Since at this location the network condition status in intermediate for the REF phone, the DUT1 and DUT2 are expected to experience degradation in the RxLev and TxLev compared to the REF phone due to the modifications. It is expected to clearly observe the difference in the levels of the implemented power control for the set of phones used for this experiment.

## 4.4 GSM 900 MHz band with channel lock

The phones were locked at GSM 900 MHz and at the channel with the best receive signal strength for the entire duration of the measurements. The measurements were performed in batches such that each batch measurement consists of 10 measurements of 10 minute duration yielding at least 1000 data points for each parameter.

On average, the REF phone exhibits a better reception compared to the other two phones. The RxLev progressively degrades as we go from REF to DUT1 and then to DUT2. Next we analyze the TxLev performance, it can be clearly observed that there are more instances of TxLev (in pink) for DUT2 being visibly higher than the TxLev (in green) of the REF phone indicating that the REF phones experiences higher level of power control due to its superior TRP performance. However the TRP performance difference between the REF phone and DUT1 is not significant enough as a result the DUT1 experiences nearly similar levels of power control as for the REF phone.

## 4.5 Spatial Verification at GSM

The investigation described above was performed for the DUT facing the window in the indoor environment. To account for non-line of sight nature of the received signal and to identify which orientation will result in a lower transmit level for the DUT, a four orientation spatial verification was performed. The DUT positioning used for the above study is considered as the 0 degrees position and the batch measurements are repeated by turning the DUT in steps of 90 degrees in the clockwise direction. Four measurements are performed for the DUT at this particular location with 10 measurements each at 0, 90, 180 and 270 degrees. This was primarily required to assess the effect of the radiation pattern on transmit and receive performance with respect to orientation. It is expected that at GSM, the radiation pattern will not have a significant effect since the radiation pattern generally exhibits horizontal plane symmetry. The spatial verification is also used to better approximate the real-life TRP by averaging the uplink transmit level over the four measured orientations. Typically, more orientations/positions are required to better describe the TRP. However, this measurement has been considered as the initial approximation, which can later be improved upon by performing measurements at orientations in steps of 30 degrees.

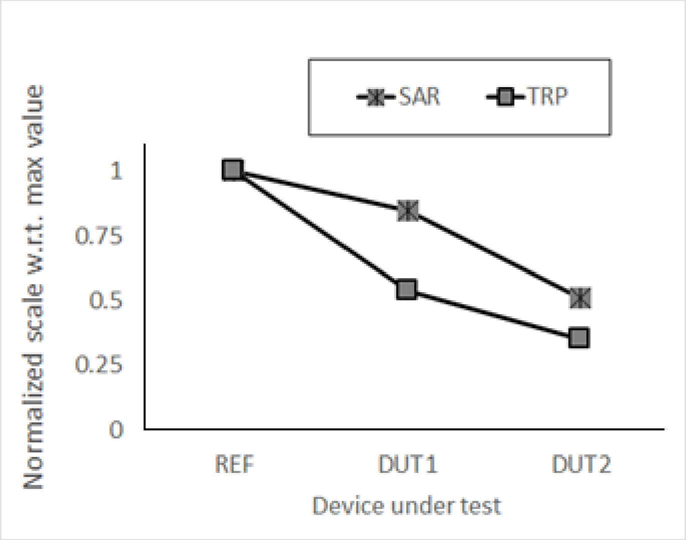


Figure 4.5-i: Normalized SAR and TRP values observed for the GSM band

With the spatial verification, a comprehensive average TxLev and RxLev profile can be generated for a particular location. The DUT can then be compared with respect to the orientations and subsequently with the average of the metrics used for comparison. The DUT have been previously characterized for their SAR and OTA performance. If an assessment of the DUT for their exposure in real-life scenarios based on their SAR characterization is to be made, then as described in Figure 4.5-i, DUT2 would be considered as the better of the three phones, followed by DUT1 and the REF being the worst of the three. Since it is known that the single point SAR value is not necessarily representative of the real-life exposure under typical usage scenarios, which in the case of these DUTs is also expected when their TRP performance is taken into account. It was observed that DUT2 has significantly degraded TRP characterization which most likely would lead to higher transmit levels under typical usage scenarios compared to the REF phone. It is expected that for a network condition classified as intermediate, the REF phone on an average would transmit at a lower power level than DUT1 and DUT2, more specifically lower than DUT2.

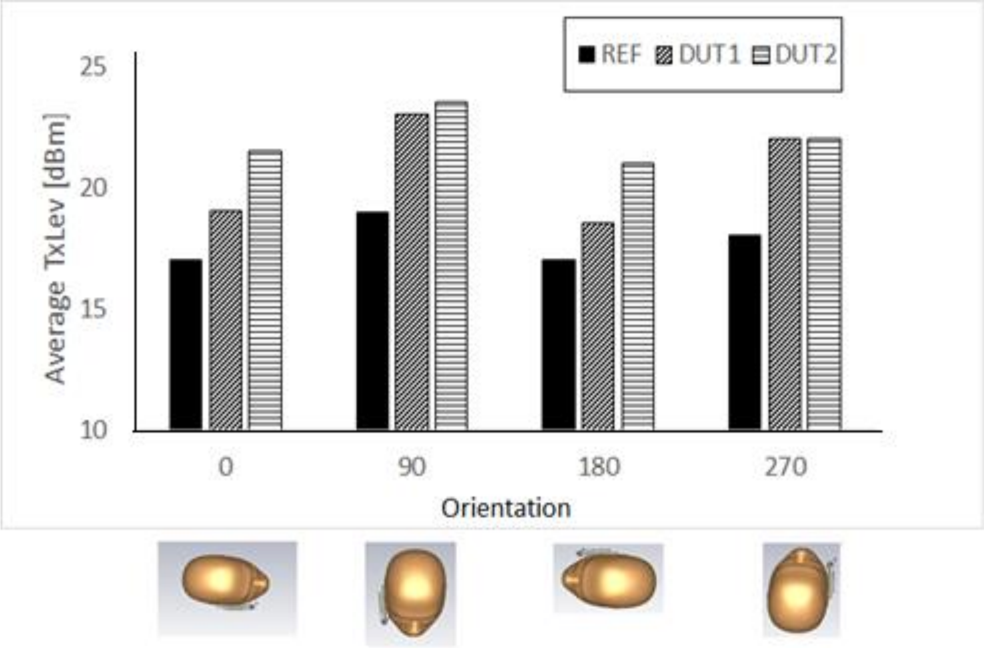


Figure 4.5-ii: The average TxLev performance of the phones at GSM for the four orientations

As observed in figure 4.5-ii, on average the REF phone transmits at a lower level compared to DUT1 and DUT2 with respect to the orientation at a particular location. DUT2 transmits at the highest transmission levels for all the orientations with DUT1 matching the transmission levels of DUT2 at 270 degrees orientation. The transmit levels for the DUTs are found to be higher for orientations 90 and 270 degrees as compared to 0 and 180 degrees. The transmit level averaged over the four orientations will provide a meaningful value compared to the transmit level measured at just one of the orientations. At this location, it can be concluded that effect of the radiation pattern with respect to the orientation on the transmit performance is not significant to affect the comparative trend among the DUT used for measurements.

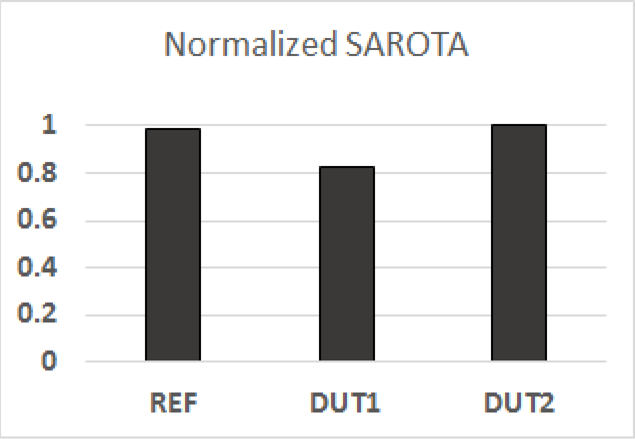


Figure 4.5-iii: Normalized SAROTA index for the GSM band

When the SAROTA index is considered as described in Figure 4.5-iii, the REF phone is predicted to exhibit a real-life exposure comparable to the real-life exposure from DUT2 while the DUT1 is expected to exhibit the lowest exposure. The TRP_real-life is calculated from the transmit level averaged over the four measured orientations and accounting for the losses in the presence of the SAM phantom. The SAR_real-life is evaluated and compared with the predicted SAROTA index. Figure 4.5-iv, presents the normalized SAROTA and SAR_real-life where it is observed that the lowest real-life SAR is observed for DUT1 followed by DUT2 and then REF. This is an important observation as the REF phone which was considered to be worst among the three for its real-life exposure based on the SAR characterization is found to exhibit a comparable real-life exposure due to DUT2 where DUT2 has a significantly lower maximum SAR value.

The SAROTA index qualitatively predicts the real-life exposure for the network condition classified as intermediate.

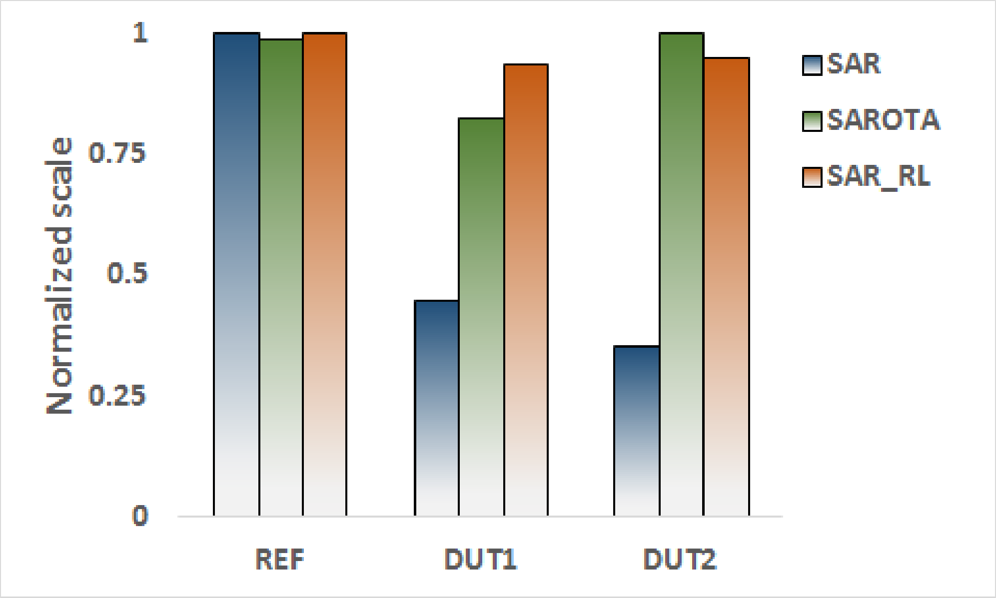


Figure 4.5-iv: Normalized SAR, SAROTA and SAR_RL values observed for the GSM band

## 4.6 DCS band with channel lock

After experimentally validating the SAROTA at GSM 900 MHz, the measurements were performed for the DCS band. The location which was with intermediate network condition status for GSM was observed to be a bad network condition for the DCS band, with only the REF phone being able to sustain the channel lock for the 10 min measurements period while both, DUT1 and DUT2 experiencing 7 out of 10 call drops. All the measured phones were observed to transmit at the maximum power level. This location was clearly not suitable to observe the effects due to the antenna modifications due to the negligible uplink power reduction observed. Coincidentally the location with network condition status good for the GSM band was observed to be the intermediate network condition for the DCS band. The batch measurements were initiated with system lock at DCS and channel lock at TCH B. TCH B was found to be the 2nd best performing channel at this location and was able to sustain the communication link on 8 out of 10 attempts. TCH A was the best performing channel but it is worth noting that it was only marginally better than TCH B (approx. 2-3 dB), however call drops of 5 out of 10 attempts were observed for TCH A. The REF phone was observed to exhibit a higher level of power control compared to DUT1 and DUT2 while DUT1 was observed to consistently transmit approximately 2dB lower compared to DUT2.

## 4.7 Spatial Verification at DCS

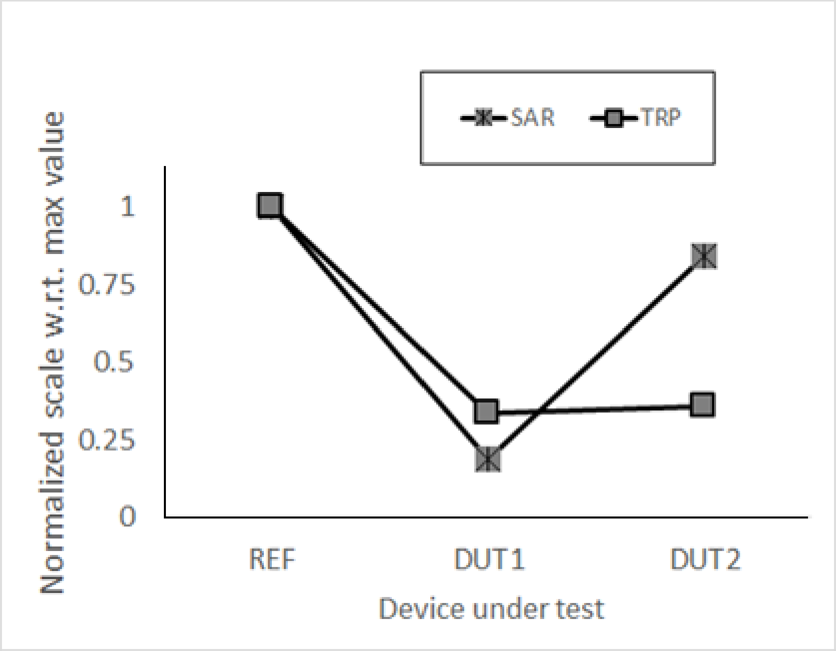


Figure 4.7-i: Normalized SAR and TRP values observed for the DCS band

Following the similar process as performed for the GSM section for selecting the phone for its real-life exposure based on the SAR characterization, then as described in figure 4.7-i, DUT1 would be considered the best phone, followed by DUT2 and the REF again (like in GSM) being the worst of the three. When the TRP performance was taken into account, it was observed that both DUT1 and DUT2 have a significantly degraded TRP characterization compared to the REF phone. It is expected that for a network condition classified as intermediate, the REF phone would on an average transmit at a lower power level than both DUT1 and DUT2, while DUT1 and DUT2 are expected to transmit at similar levels.

As observed in figure 4.7-ii, on an average the REF phone was observed to transmit at a lower level compared to DUT1 and DUT2 with respect to the orientation at a particular location. Both DUT1 and DUT2 transmit at similar levels for all the orientations except at 270 degrees orientation where DUT1 transmits at maximum power while DUT2 undergoes observable power control. It is worth noting that both DUT1 and DUT2 exhibit on an average near maximum transmit levels while the REF phone undergoes power control in the range of 5 to 7 dB across all orientations. At this location, it can be concluded that effect of the radiation pattern on the transmit performance is visible specifically at 270 degrees where the DUT2 experiences power control while DUT1 does not undergo power control.

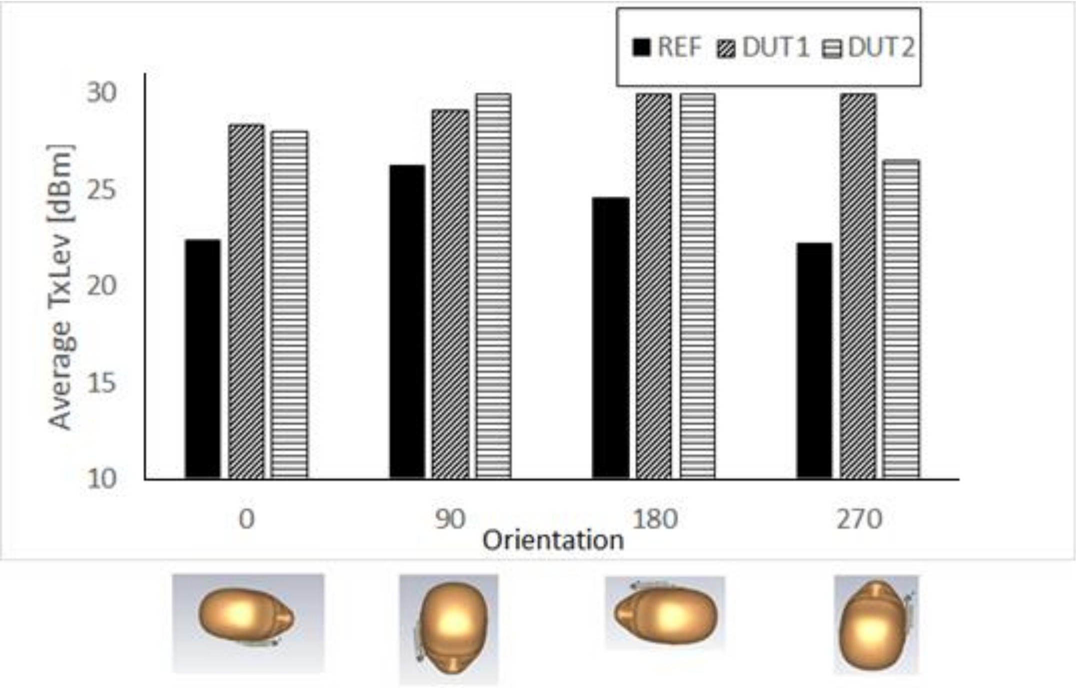


Figure 4.7-ii: The avg. TxLev performance of the phones at DCS for the four orientations.

Observing the SAROTA index described in figure 4.7-iii, DUT1 is predicted to exhibit the lowest real-life exposure followed by the REF phone while the DUT2 is expected to exhibit the highest exposure among the three phones. As in the case of GSM, the TRP_real-life is calculated from the transmit level averaged over the four measured orientations and accounting for the losses in the presence of the SAM phantom. The SAR_real-life is evaluated and compared with the predicted SAROTA index, as expected we observe that the lowest real-life SAR is observed for DUT1 followed by the REF phone and then DUT2. The REF phone which was considered to be worst among the three for it real-life exposure based on the SAR characterization, exhibits nearly 60% lower real-life exposure compared to DUT2 which exhibits the highest real-life exposure in comparison. It should be noted that though DUT1 is classified as the phone with the least exposure, due to its poor TRP performance, it is observed to be transmitting at near maximum level which will eventually adversely affect the battery life of the phone. The REF phone on the other hand exhibits marginally higher exposure but due to its superior TRP performance will have the advantage in terms of battery life during typical usage scenarios

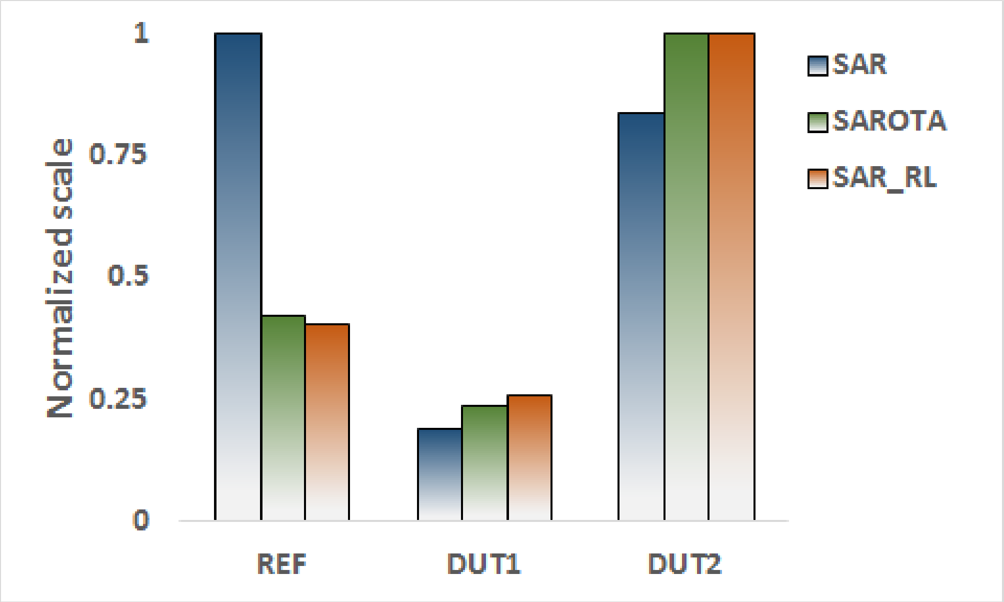


Figure 4.7-iii**:** Normalized SAR, SAROTA and SAR_RL values observed for the DCS band

The SAROTA index qualitatively predicts the real-life exposure at DCS for the network condition classified as intermediate.

## 4.8 Spatial Verification at UMTS is currently under investigation

After experimentally validating the SAROTA at GSM and DCS bands, the measurements were performed for the UMTS band. The identification of the network conditions and finding a suitable location for the UMTS band was observed to be more challenging than GSM and DCS. This is primarily due to the difference in the operation techniques of the two systems where the UMTS power control has a very large dynamic range, approximately 80 dB in the uplink. Also the nature of the power control algorithms differ significantly. UMTS is capable of fast power control where the uplink transmit power can be adjust more rapidly than in GSM with much finer step sizes (range from 0.5 dB, 1dB and 2dB). To perform the measurements the DUTs were locked to the UMTS system and the carrier lock feature was utilized.

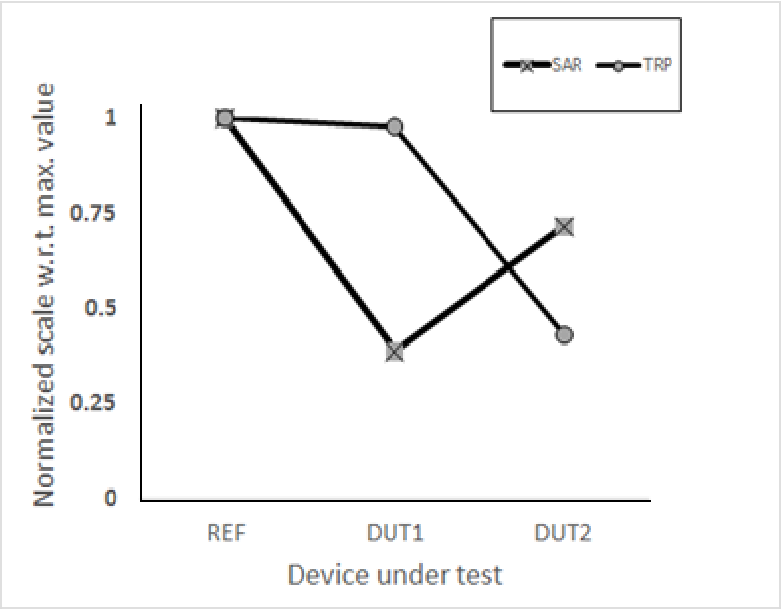


Figure 4.8-i: Normalized SAR and TRP values observed for the UMTS band

From figure 4.8-I, if the phones are selected based on the SAR characterization to imply the real-life exposure will be less for a phone with a lesser SAR, the following assumptions will follow: DUT1 would be considered the best phone, followed by DUT2 and then REF again (like in GSM) being the worst of the three. When we take into account the TRP performance, it is observed that both REF and DUT1 exhibit similar TRP levels while DUT2 exhibits a significantly degraded TRP characterization compared to the REF and DUT1. It is expected that for a network condition classified as intermediate, the DUT2 will on an average transmit at a higher power level than both REF and DUT1, while REF and DUT1 are expected to transmit at similar levels.

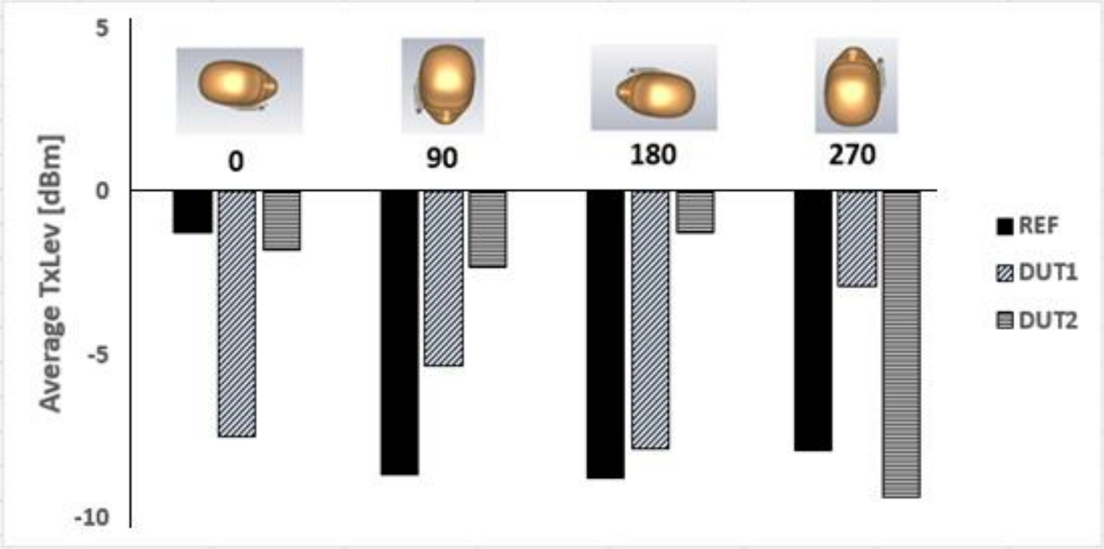


Figure 4.8-ii: The avg. TxLev performance of the phones at UMTS for the four orientations.

Figure 4.8-ii, describes TxLev and the RxLev experimental results for the UMTS band. The REF and DUT1 transmit levels averaged over the four orientations exhibit nearly similar transmit levels while DUT2 consistently transmits at higher power.

When we consider the SAROTA index described in Fig.4.8-iii, DUT1 is predicted to exhibit the lowest real-life exposure followed by REF while the DUT2 is expected to exhibit the highest exposure in comparison. The TRP_real-life is calculated from the transmit level averaged over the four measured orientations and accounting for the losses in the presence of the SAM phantom. The SAR_real-life is evaluated and compared with the predicted SAROTA index, as expected we observe that the lowest real-life SAR is observed for the DUT1 followed by REF and then DUT2. This is an important observation as the REF phone which has a highest

SAR value among the three, it is found to exhibit lower real-life exposure in a real-life scenario than DUT2 which has a lower SAR value than the REF.

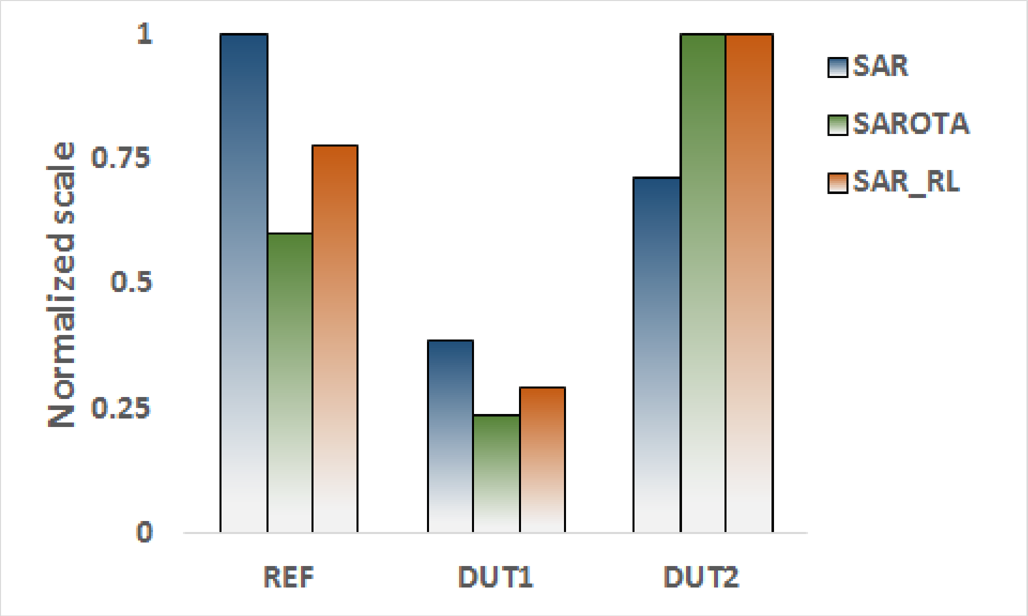


Figure 4.8-iii: Normalized SAR, SAROTA and SAR_RL values observed for the UMTS band

The SAROTA index qualitatively predicts the real-life exposure for the network condition classified as intermediate.

## 4.9 Summary

It should be noted that the measurements for GSM, DCS and UMTS were performed at different indoor locations where the intermediate network condition could be approximated. The intermediate network condition is classified with respect to the received signal strength levels observed for the REF phone and also the call connectivity capability of the phone with the poorest TRP. The average TxLev value is obtained by performing 10 measurements at each orientation (0, 90, 180, 270 degrees) i.e. a total of 40 measurements per phone at one particular location for GSM, DCS and UMTS respectively. The individual characterization at GSM, DCS and

UMTS can be used to assess the exposure for a phone operating without the system lock where it is free to change between GSM, DCS and UMTS.

The average TxLev values confirm that the phone with a superior TRP performance is able to sustain the call with a lower transmit level compared to the phones with a comparatively degraded TRP performance. The TRP_real-life values represent the TRP required to satisfactorily sustain the communication at that particular location. The TRP_real-life and the average TxLev indicate the extent of power control implemented for each phone. It clearly shows that the phone with a superior TRP performance experiences a higher level of power control or a higher reduction in the transmit levels in a real-life scenario. The SAR_real-life is always lower than the SAR measured under laboratory conditions when the implementation of power control level is observed. Higher power control implies lower uplink transmit levels and a lower SAR_real-life. This implies that the phones with superior TRP performance have a higher chance of experiencing power control and thus lowering of real-life exposure compared to the stated SAR value.

The SAROTA index can be used for personal exposure assessment to the user in the uplink where the exposure is localized near the head region. This can supplement the exposimetry data where the current exposimeters have limitations in measuring the exposure near the head region with the required accuracy.

With the present SAROTA formulation, it can be used as a user level exposure metric using which a comparable RF exposure estimate can be made to assess a set of phones substantially differing in the TRP performance.

# Chapter 5

# Conclusion and Perspectives

## 5.1 Conclusion

The indoor environment can be characterized reliably for the GSM and DCS bands to perform targeted measurements with sufficiently high repeatability as the network parameters set by the network operators are observed to be fairly stable.

The average transmit power levels are also dependent on the number of channel changes. Each channel change is conducted according to the specified handover protocol in GSM where high transmit power is to be maintained while switching form one channel to another and the power control can only be initiated after the successful channel change. This implies a call placed ( on a GSM network) on a phone where both power control and a large number of channel changes are observed will exhibit a higher average transmit power level when the same phone experiences lesser number of channel changes.

Characterizing the indoor environment for the UMTS band was observed to be more challenging than for GSM and DCS band. The repeated baseline measurements to characterize the downlink parameters are essential for performing measurements at UMTS.

Under similar conditions where power control is possible, a mobile phone with the hand phantom generally exhibits a higher real-life exposure (more than or equal to 2 times which) compared to when measuring the same phone without hand at GSM and DCS. This is valid for cases where the hand phantom degrades the TRP performance of the mobile phone by more than 2 dB.

This conclusion is stated on the basis that the presence of the hand adversely affects the TRP performance of the mobile phone in most cases. Considering the OTA uncertainty of 2dB for the measurement setup is valid for the all the phones used in this study. The results are “consistently repeatable” for the TCH at which the phones have been evaluated in the characterized environment. This condition has not been tested for the cases where the TRP performance is not adversely affected by the presence of the hand. The study is performed with the same phone with and without the hand phantom. The use of MIMO technology to mitigate the TRP degradation needs to be investigated.

SAR characterization with hand phantom might result in a lower value than without. The SAROTA index derived from SAR and TRP data for the given scenario rightly predicts (qualitatively but not yet quantitatively) a higher exposure for the phone used with the hand phantom.

The SAROTA index is evaluated for the same configuration for which the SAR and TRP are measured. Since the use of hand is presently not mandatory for the SAR characterization, the hand phantom was not used in the last phase of the study. The cases for which the TRP of the phones is degraded by the presence of the hand a corresponding decrease in the SAR value is generally observed (unless there is drastic redistribution compared to the initial SAR pattern). For cases where the SAR is increased with the presence of the hand, the TRP is likely to not be adversely affected. This preserves the SAR and TRP relation. The focus was therefore restricted to the effect of TRP on the observed power control.

The assumption that the mobile phone with a lower SAR always results in a lower real -life exposure without considering the OTA performance is observed to be false for the network and measurement conditions described for the effect of the hand phantom experiment.

The phone with the best TRP performance indeed experiences a higher degree of power control compared to the phones with comparatively poor TRP performance.

A method to determine the real-life exposure at a particular indoor location using the four orientation spatial characterization to approximate the TRP during live calls is experimentally validated.

The capability of the SAROTA index to compare mobile phones with sufficiently different TRP values is demonstrated for the GSM, DCS and UMTS bands for a network condition characterized as intermediate (where the received signal strength can be considered to be between good and poor coverage conditions).

## 5.2 Perspectives

The study is based on the speech mode of operation of the mobile phones. The study can be extended to include the data mode of operation.

A mobile application can be developed to evaluate the SARreal-life where the user can enter the data related to the mobile usage position while an internal database will contain the SAR and TRP values for various configurations. The average SARreal-life could be calculated over a certain period such as days, weeks, months for certain usage configurations.

The available software modifies phones are 2G and 3G compatible and the work undertaken provides reliable measurements for the GSM and DCS bands representing 2G. The present status of the work completed for the UMTS band representing 3G exhibits the possibility of extending to include various indoor scenarios.

The work can be extended to the LTE band by acquiring a diverse set of software modified smartphones.

The study can be extended to characterize various hand phantom grips to assess their effect on the TRP performance in a live radio network for both the speech and data mode of operation.

The first approximation numerical model developed for one of the SMP can be developed further to make it more representative of the real world model to perform various future experiments.

# REFERENCES

[1] W. Roach, “Radio Frequency Radiation Dosimetry Handbook”, 5th edition.

[2] ICNIRP, “Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)”, Health Physics, 1998, 74,494-522.

[3] IEEE standard C95.7-2005, “IEEE Recommended Practice for Radiofrequency Safety Programs.”, New York, 2005.

[4] P. Frei, E. Mohler, G. Neubauer , G. Theis et al ,” Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields”, Environ Res. 2009, 109(6):779-85. doi: 10.1016/j.envres.2009.04.015.

[5] W. Joseph, P. Frei, G. Vermeeren, L. Martens et al , “Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe”, Environ Res. 2010 Oct;110(7):658-63. doi: 10.1016/j.envres.2010.06.009.

[6] P. Frei, E. Mohler, A. Burgi, et al, “Classification of personal exposure to radio frequency electromagnetic fields (RF-EMF) for epidemiological research: Evaluation of different exposure assessment methods”, Environ Int. 2010 Oct, 36(7):714-20. doi: 10.1016/j.envint.2010.05.005.

[7] A. Ahlbom, A. Green, L. Kheifets, D. Savitz, A. Swerdlow,“Epidemiology of health effects of radiofrequency exposure” Environ Health Perspect 1121741–1754.175410.1289/ehp.7306, 2004.

[8] P. Frei, M. Roosli, E. Mohler, K. Hug, “Systematic review on the health effects of exposure to radiofrequency electromagnetic fields from mobile phone base stations”, Bulletin of the World Health Organization 2010;88:887-896F. doi: 10.2471/BLT.09.071852.

[9] M. Dahme, “Residential RF exposures”, Radiat Prot Dosimetry, 1999, 83:113–117.

[10] J. Schüz, S. Mann, “A discussion of potential exposure metrics for use in epidemiological studies on human exposure to radiowaves from mobile phone base stations”, J Expo Anal Environ Epidemiol 10:600–605, 2000.

[11] LS. Goldstein, L. Kheifets, E. van Deventer, M. Repacholi, “Long-term exposure of Emicro-Pim1 trans-genic mice to 898.4 MHz microwaves does not

increase lymphoma incidence” by Utteridge et al., Radiat. Res. 158,357–364 (2002). Radiat Res 159:275–276.

[12] D. Krewski, C. Byus, B. Glickman, et al. 2001. Potential health risks of radiofrequency fields from wireless telecommunication devices. J Toxicol Environ Health B Crit Rev 4:1–143.

[13] CENELEC Standard ENS 50361: "Basic Standard for the measurement of Specific Absorption Rate related to human exposure to electromagnetic fields from mobile phones (300 MHz-3 GHz)", Brussels, Belgium, CENELEC, July 2001, 51 p.

[14] IEC standard 106 PT62209 part 1 Ed. 1.0: "Procedure to measure the Specific Absorption Rate (SAR) in the frequency range of 300 MHz to 3 GHz - Part 1: hand-held mobile wireless communication devices"

[15] IEEE standard P1528; "Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Experimental Techniques", April, 2003.

[16] Universal Mobile Telecommunications System (UMTS), Specific Absorption Rate (SAR) requirements and regulations in different regions (3G TR 34.925 version 3.0.0 Release 1999).

[17] C. Gordon, C. Churchill et al, “Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics”, Technical Report NATICK/TR-89/044, U.S. Army Natick Research, Development and Engineering Center, Natick, Massachusetts, Sep. 1989.

[18] M.Y. Kanda, M. Ballen, C.K, Chou. "Formulation and characterization of tissue simulating liquids used for SAR measurement (500-2000 MHz)" Asia-Pacific Radio Science Conference, Tokyo, Japan, August 1-4, 2001, p. 274.

[19] V. Vigneras, "Elaboration and characterization of biological tissues equivalent liquids in the frequency range 0.9 - 3 GHz", Final report, PIOM Laboratory, University of Bordeaux, France, November 2001.

[20] CTIA Certification: “Test plan for mobile station over the air performance Rev.2.2”

[21] 3GPP TS 25.101 V4.10.0: "User Equipment (UE) radio transmission and reception (FDD)".

[22] 3GPP TR 25.914 V.1.0.0: “Measurements of radio performances for UMTS terminals in speech Mode.”

[23] 3GPP TS 34.114 V.7.0.0: “User Equipment (UE) / Mobile Station (MS) Over-The -Air (OTA) antenna performance; Conformance testing (Release 7).”

[24] K. Rosengren, P-S. Kildal, C. Carlsson, J. Carlsson, "Characterization of antennas for mobile and wireless terminals in reverberation chambers: Improved accuracy by platform stirring, Microwave and Optical Technology Letters, Vol. 30, No 20, pp.391-397, Sep. 2001.

[25] P-S. Kildal, C. Carlsson, "Detection of a polarization imbalance in reverberation chambers and how to remove it by polarization stirring when measuring antenna efficiencies", Microwave and Optical Technology Letters, Vol. 34, No. 2, pp 145-149, July 20, 2002.

[26] Y. Okano, D. Kurita, S. Nakamatsu, T. Okada, “Evaluation of OTA performance for mobile terminal antennas reflecting practical usage and improvement of measurement efficiency”, NTT DOCOMO Technical Journal vol. 11 no.2.

[27] Digital cellular telecommunications system (Phase 2+) Radio transmission and reception (3GPP TS 45.005 version 11.4.0 Release 11).

[28] Digital cellular telecommunications system (Phase 2+) Radio subsystem link control (3GPP TS 45.008 version 11.5.0 Release 11).

[29] F. Gunnarsson, F. Gustafsson, Control theory aspects of power control in UMTS, Control Engineering Practice, Volume 11, Issue 10, Pages 1113-1125, October 2003.

[30] H. Holma, A.Toskala (editors), "WCDMA for UMTS: Radio Access for Third Generation Mobile Communications", John Wiley & Sons Ltd 2000, ISBN 0-471-72051-8, 322 p.

[31] M. Chiang, P. Hande, T. Lan, C. W. Tan, “Power Control in Wireless Cellular Networks”, Now Publishers, 2008.

[32] Outer-Loop Power Control in a Live UMTS Network: Measurement, Analysis and Improvements, ISCCSP 2010, Limas-sol, Cyprus, 3-5 march 2010.

[33] V. Monebhurrun, “A real-life exposure evaluation index for mobile phones based on SAR and TRP measurements data: the SAROTA index,” in Proc. BEMS 2010, Seoul, 14-18 June 2010.

[34] N. Varsier et al, “Exposure index of EU project LEXNET: principles and simulation-based computation”, EUCAP 2014, p.3029-3032, http://hdl.handle.net/1854/LU-5816590

[35] A. Rojatkar and V. Monebhurrun, “Experimental evaluation of the SAROTA concept for the evaluation of the real-life exposure due to mobile phones,” BEMS 2013, Thessaloniki, 10-14 June 2013, 2 pages on CD.

[36] A. Rojatkar and V. Monebhurrun, “Evaluation of the Real Life Exposure due to GSM Mobile Phones,” URSI GASS 2014, Beijing, China, 16-23 August 2014.

[37] A. Rojatkar and V. Monebhurrun, “Application of the SAROTA concept in real-life scenario” IOP Conf. Series: Materials Science and Engineering, 2014, 67 pp.012020, DOI:10.1088/1757-899X/67/1/012020.

[38] A. Rojatkar and V. Monebhurrun, “Investigation of the effect of the hand on the real-life performance of mobile phones,” BioEM 2014, Cape Town, South Africa, 8-13 June 2014.

[39] N. T. Atanasov and G. L. Atanasova, “An investigation of the effects from the user’s hand and head over received level and adaptive power control of a GSM mobile phone is typical operating environment,” The Environmentalist, Vol. 27, Issue 4, Dec. 2007, pp. 585-591.

[40] C. H. Li, M. Douglas, E. Ofli, B. Derat, S. Gabriel, N. Chavannes, N. Kuster, “Influence of the Hand on the Specific Absorption Rate in the Head”, IEEE Transactions on Antennas and Propagation 2012, Vol. 60, Issue.2, pp. 1066 - 1074, doi: 10.1109/TAP.2011.2173102.

[41] O. Colas, C. Dale, J. Wiart "Influence of hand on the terminal total radiated power" COST 273 TD(04) 057.

[42] T. Weiland, “RF & Microwave simulators – From component to system design”, Microwave conf. 2003, vol. 2, pp. 591-596, doi: 10.1109/EUMC.2003.1262960.

[43] O. Kivekas, J. Ollikainen, T. Lehtiniemi, and P. Vainikainen, “Bandwidth, SAR, and efficiency of internal mobile phone antennas,” IEEE Transactions on Electromagnetic Compatibility, vol. 46, no. 1, pp. 71–86, 2004.

[44] V. Monebhurrun et al, “Numerical and experimental investigations of a commercial mobile handset for SAR calculations”, in Proc. 2nd Int. Conf. Bioinformat. Biomed. Eng., May 2008pp. 784–787.

[45] V. Monebhurrun et al, “A benchmark CAD mobile phone model for specific absorption rate calculations”, IEEE Transactions on Magnetics, 50, 2, 2014, pp. 1-4.

[46] M. Siegbahn et al, “An international interlaboratory comparison of mobile phone SAR calculation with CAD-based models,” IEEE Transactions on Electromagnetic Compatibility, 52, 4, 2010, pp. 804-811.

[47] A. Rojatkar and V. Monebhurrun, “Experimental validation of the numerical model of a commercial mobile phone for specific absorption rate assessment” APSYM 2014, Cochin, India, 17-19 December 2014.

[48] V. Monebhurrun , X.Cheng and A. Rojatkar, “Calibration of the CAD model of a commercial mobile phone for SAR compliance” BioEM 2015, California, USA, 14-19 June 2015.

[49] V. Monebhurrun , X.Cheng and A. Rojatkar, “CAD mobile phone model calibration using experimental specific absorption rate data” RADIO 2015, 21-24 Sept 2015, DOI:10.1109/RADIO.2015.7323405.

[50] 3GPP TR 25.144 V.11.2.0 Release 11: “Universal Mobile Telecommunication System (UMTS); User Equipment (UE) and Mobile Station (MS) over the air performance requirements”, pp 10, 21.

[51] T. Taga, "Analysis for mean effective gain of mobile antennas in land mobile radio environments", IEEE Transactions on Vehicular Technology, 39(2): 117-131, May 1990.

[52] K. Kalliola, K. Sulonen. H. Laitinen, O. Kivekäs, J. Krogerus, and P. Vainikainen, "Angular power distribution and mean effective gain of mobile antenna in different propagation environments", IEEE Transactions on Vehicular Technology, 51(5): 823-838, September 2002.

[53] Alayon Glazunov, A., Pasalic, E., "Comparison of MEG and TRPG of practical Antennas", in Proc. of PIMRC'04-15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Barcelona Spain, Sept. 2004

[54] J. Oedum Nielsen, "Comparison of Total Received Power and Mean Effective Gain for Mobile Handsets", COST273 TD (02) 021.

[55] CST: http://www.cst.com

[56] "Guide to the Expression of Uncertainty in Measurement", International Organization for Standardization (ISO), Geneva, Switzerland 1995.

[57] Décret no 2010-1207 du 12 octobre 2010 relatif à l’affichage du débit d’absorption spécifique des équipements terminaux radioélectriques, JORF no 0239 du 14 octobre 2010 page 18463, texte no 34.

[58] Anite Nemo Handy : http://www.anite.com/businesses/network-testing/products/nemo-handy-world%E2%80%99s-most-widely-used-handheld-drive-test-tool

université
PARIS-SACLAY

ÉCOLE DOCTORALE
Physique et ingénierie :
électrons, photons,
sciences du vivant (EOBE)

**Titre :** Développement d'une méthodologie pour l'évaluation de l'exposition réelle des personnes aux champs électromagnétiques

**Mots clés :** Exposition RF, Débit d'absorption spécifique, SAROTA, Téléphone mobile, contrôle de puissance, Puissance totale rayonnée.

**Résumé :** Le travail présenté dans cette thèse a pour objectif l'étude des conditions nécessaires pour évaluer l'exposition radio fréquence (RF) due aux téléphones mobiles dans un scenario d'utilisation réelle et le développement d'une méthodologie permettant de prédire et de comparer les téléphones mobiles en fonction de leurs expositions RF réelles. Les téléphones mobiles sont caractérisés par leur débit d'absorption spécifique (DAS) et leur performance en émission et en réception (over-the-air, OTA). En utilisant le DAS et la puissance totale rayonnée (PTR), un indice d'exposition appelée l'indice SAROTA a été proposé précédemment afin de prévoir l'exposition réelle des téléphones mobiles. L'indice SAROTA sert ainsi de métrique permettant de comparer les téléphones mobiles. Lors d'une première phase de l'étude, la stabilité de l'environnement intérieur a été évaluée. Lors d'une deuxième phase, l'influence de la main sur le DAS et la PTR des téléphones mobiles ainsi que sur l'évaluation de l'exposition réelle prédite par l'indice SAROTA a été étudiée. Lors d'une troisième phase, un ensemble de téléphones mobiles identiques ont été modifiés et des mesures effectuées pour vérifier que l'indice SAROTA permet bien de prédire l'exposition réelle des personnes.

**Title :** Developement of a methodology for the assessment of real-life exposure due to electromagnetic fields.

**Keywords :** RF exposure, Specific absorption rate, SAROTA, Mobile phones, Power control, Total radiated power.

**Abstract :** The thesis describes the need for assessment of radio frequency (RF) exposure due to mobile phones under typical usage/ real-life scenarios and to develop a method to predict and compare mobile phones for their real-life RF exposure. The mobile phones are characterized for their specific absorption rate (SAR) and for transmit and receive performance given by the over-the-air (OTA) characterization. Using the SAR and the total radiated power (TRP) characterization, an exposure index referred to as the SAROTA index was previously proposed to predict and compare the real-life exposure. In the first phase of the study, the stability of the indoor environment was evaluated. During the second phase, the influence of hand phantom on the SAR and TRP of the mobile phones and the capability of the SAROTA index to predict the exposure was investigated. In the third phase, a set of identical software modified phones were externally modified to alter the TRP performance and the methodology to determine the real-life exposure and also verify the capability of the SAROTA index to predict the exposure levels was investigated. The experiments demonstrate that the SAROTA index is capable of predicting the real-life exposure and comparing the mobile phones.

**Université Paris-Saclay**
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France