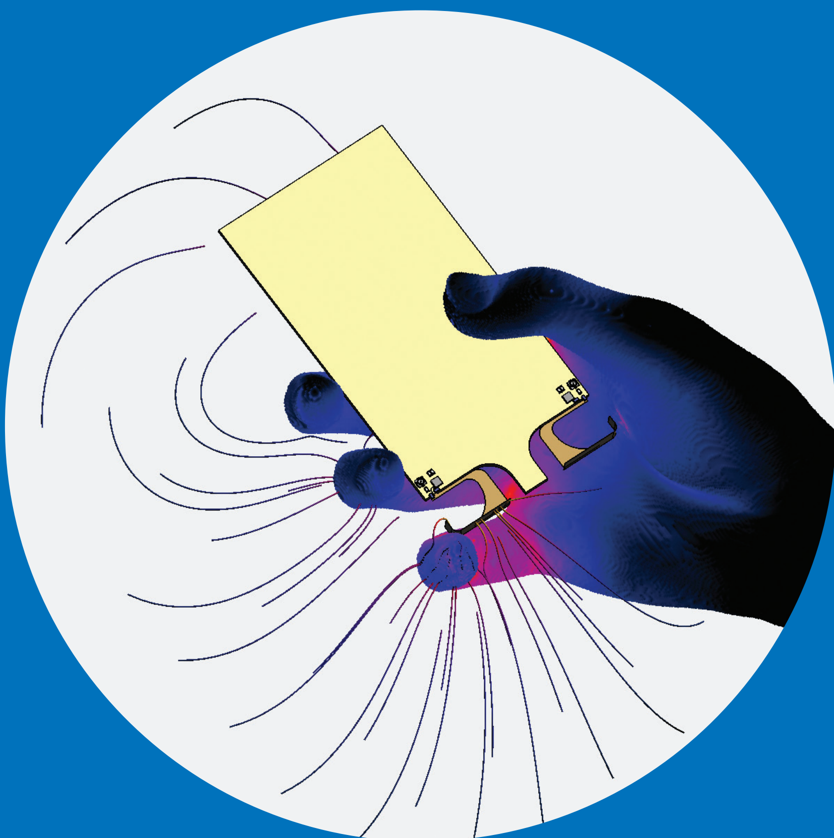
Department of Radio Science and Engineering

Multiband and environment insensitive handset antennas

Janne Ilvonen



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Multiband and environment insensitive handset antennas

Janne Ilvonen

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Aalto University
School of Electrical Engineering
Department of Radio Science and Engineering

Supervising professors
Prof. Pertti Vainikainen, until June 30, 2012
Assist. Prof. Ville Viikari, as of October 25, 2012

Thesis advisors
D.Sc. (Tech.) Outi Kivekäs, until May 31, 2011
Univ. Lect. Jari Holopainen, as of March 16, 2012

Preliminary examiners
Prof. Dr.-Ing. Dirk Heberling, RWTH Aachen University, Germany
D.Sc. (Tech.) Jani Ollikainen, Nokia Corporation, Finland

Opponent
Assoc. Prof. Buon Kiong Lau, Lund University, Sweden

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Abstract

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Abstract

The number of antennas in small handsets has been increasing, while the volume reserved for the antennas has remained the same or even reduced. Consequently, antennas become easily inefficient, thereby lowering the data rate and coverage. An additional challenge is that the antenna should be insensitive to the way the handset is held by the user. The results of this doctoral thesis can be used to develop small-sized, multiband and efficient handset antennas with good robustness against environmental changes caused for instance by the user's hand.

The first part of the thesis introduces novel handset antennas that have state-of-the-art performance in terms of antenna volume, impedance bandwidth and efficiency. A design strategy for 4th generation (4G) handset antennas and a new method to analyze the suitability of an antenna geometry for frequency tuning are introduced. Furthermore, a novel tunable handset antenna with Multiple-Input Multiple-Output (MIMO) capability is presented. The total efficiency of the proposed tunable MIMO antenna is shown to be better than 49% across the frequencies of 698–960 MHz and better than 56% across the frequencies of 1430–2690 MHz when MicroElectroMechanical System (MEMS)-based digitally tunable capacitors are used. Finally, an effective method to achieve up to 100 dB port-to-port isolation is proposed.

Different user-related challenges of handset antennas are discussed in the second part of this thesis. It is shown that a part of the hand losses can be avoided with a clever antenna design. This part also discusses the benefits and drawbacks of using either compact or large-sized antennas. A small-sized antenna can be more tolerant to user-originated losses than a large-sized antenna when an effective frequency tuning method is used. Furthermore, design aspects for gaining a good multi-antenna performance with the user are discussed.

Novel methods to reduce the electromagnetic exposure and the interaction between a user and a mobile handset antenna are discussed in the third part. The thesis gives the first analysis of feasibility of balanced antennas for handsets. Moreover, a novel shielding method to decrease the specific absorption rate (SAR) in the head by 81% and to improve the total efficiency by 5 dB is introduced. In the end of the thesis, a method is proposed to weaken the near-fields of handset antenna: wavetraps can be used to reduce, for example, electric field by up to 75%, resulting in improved hearing-aid compatibility (HAC) and SAR.

Keywords balanced antenna, capacitive coupling element, frequency tuning, MIMO systems, mobile antennas, multiple antennas, user effect

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Tiivistelmä

Matkapuhelinantennien suunnittelussa suurimmat haasteet liittyvät antennien fyysiseen kokoon ja käyttäjän vaikutukseen. Antennien lukumäärä matkapuhelimissa on lisääntynyt antenneille varatun tilavuuden pysyessä ennallaan tai jopa pienentyessä. Tämän seurauksena muun muassa antennien hyötysuhteet, saavutettavissa olevat tiedonsiirtonopeudet, sekä kantamat ovat laskeneet. Antennien on myös toimittava tehokkaasti erilaisissa ympäristöissä, esimerkiksi käden tai pään läheisyydessä. Tämän väitöskirjan tuloksia voidaan käyttää kehitettäessä pienikokoisia ja monikaistaisia antenneja, joilla on hyvä hyötysuhde myös esimerkiksi käyttäjän käden läheisyydessä.

Työn ensimmäisessä osassa esitellään uudentyyppisiä matkapuhelinantenneja, joilla on korkea säteilyhyötysuhde antennin kokoon ja kaistanleveyteen nähden. Työssä esitellään suunnittelusäännöt neljännen sukupolven (4G) antenneille sekä menetelmä, jolla voidaan tutkia antennigeometrian soveltuvuutta taajuusviritettäviin järjestelmiin. Lisäksi esitellään taajuusviritettävä monielementtinen MIMO-antenni. Käytettäessä mikroelektromekaanisia (MEMS) digitaalisesti säädettäviä kondensaattoreita antennin alakaistan (698–960 MHz) hyötysuhteeksi saadaan parempi kuin 49 % ja yläkaistan (1430–2690 MHz) parempi kuin 56 %. Ensimmäisen osan lopuksi esitellään rakenne, jolla voidaan saavuttaa erinomainen, jopa 100 dB:n isolaatio antennien porttien välillä.

Toisessa osassa käsitellään käyttäjästä aiheutuvia matkapuhelinantennin suunnitteluhaasteita. Työssä osoitetaan, että järkevällä antennisuunnittelulla osa käyttäjän käden aiheuttamista häviöistä voidaan välttää. Tässä osassa vertaillaan keskenään myös pieni- ja suurikokoisia antenneja ja osoitetaan, että pienikokoinen antenni on usein vähemmän herkkä käyttäjästä aiheutuville häviöille kuin suurikokoinen antenni. Lisäksi pohditaan moniantennijärjestelmien suunnittelunäkökohtia, joiden avulla hyvä suorituskyky voidaan saavuttaa myös käyttäjän läheisyydessä

Kolmannessa osassa esitetään uusia tapoja vähentää sähkömagneettista altistumista ja vuorovaikutusta käyttäjän ja antennin välillä. Työssä on ensimmäistä kertaa tutkittu balansoitujen antennien soveltuvuutta matkapuhelimiin. Lisäksi esitellään uudentyyppinen antennirakenne, jolla voidaan pienentää päähän kohdistuvaa ominaisabsorptionopeutta (SAR) jopa 81 % sekä parantaa säteilyhyötysuhdetta 5 dB verrattuna perinteiseen antennirakenteeseen. Lopuksi työssä esitetään uudentyyppinen aaltoloukkuihin perustuva rakenne, jolla voidaan pienentää merkittävästi puhelimen lähikenttiä.

Avainsanat balansoidut antennit, kapasitiivinen kytkentäelementti, käyttäjän vaikutus, mobiiliantennit, monielementtijärjestelmät, taajuusviritys

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Preface

The work of this thesis has been carried out during September 2009 – May 2014 at the Department of Radio Science and Engineering in Aalto University School of Electrical Engineering. I would like to thank my first supervisor, the late Professor Pertti Vainikainen for the opportunity to work on this interesting research topic. He was one of the pioneers in the field of handset antennas, and I miss our thoughtful discussions. I am also deeply grateful to my second supervisor, Assistant Professor Ville Viikari. His ability to innovate is something incredible, and he has motivated me a lot in my own research.

My first instructor Dr. Outi Kivekäs deserves my deepest gratitude for her excellent guidance given at the beginning of my postgraduate studies. I also wish to express my sincere gratitude to my second instructor and workmate, Dr. Jari Holopainen. His desire to share his knowledge is something extraordinary.

I am grateful to my colleague Dr. Risto Valkonen for his valuable comments and his great companionship at work, leisure and during our business trips. Dr. Clemens Icheln deserves warm thanks for hiring me as a research assistant in spring 2008. Eventually it led to this thesis. In addition, I thank Mr. Kimmo Rasilainen for his excellent instruction in correct writing and for our inspiring technical discussions. I would also like to thank Ms. Anu Lehtovuori and Dr. Azremi Abdullah Al-Hadi for fruitful co-operation. And of course, I want to thank my current and former colleagues in RAD; Aki, Katsu, Afroza, Jan, Antti, Aleksi, Mikko, Vasilii, Eino, Viki, Late, Lorenz, and many more for a very enjoyable working atmosphere.

I highly appreciate the contribution of the preliminary examiners, Professor Dirk Heberling and Dr. Jani Ollikainen. Their valuable comments and suggestions have certainly improved the quality of this thesis.

The work has been partly financed by the Finnish Technology Agency (TEKES), the Academy of Finland through the Centre of Excellence program (SMARAD), and Finnish telecommunications industry. During this thesis, I have received personal financial support from the Nokia Foundation and the Finnish Society of Electronics Engineers. All this support is gratefully acknowledged.

I would like to thank my parents, Ritva and Jouko for their encouragement and all kind of support during the years. I am also thankful to my siblings Sanna, Hannu and Tommi for their encouragement during my long studies.

Finally, and most of all, my loving and caring fiancée Katriina deserves special thanks for her support and patience during the work. I look forward to her doctoral defense☺ Also our children Maria and Heikki deserve a really big hug for their understanding and love. I promise to spend more time with you!

November 5, 2014,

Janne Ilvonen

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I J. Ilvonen, R. Valkonen, J. Holopainen, and V. Viikari, "Design Strategy for 4G Handset Antennas and a Multiband Hybrid Antenna," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 4, pp. 1918–1927, April 2014.

II J. Ilvonen, R. Valkonen, J. Holopainen, and V. Viikari, "Multiband Frequency Reconfigurable 4G Handset Antenna with MIMO Capability," *Progress In Electromagnetics Research*, vol. 148, pp. 233–243, 2014.

III J. Ilvonen, O. Kivekäs, A.A.H. Azremi, J. Holopainen, R. Valkonen, and P. Vainikainen, "Isolation Improvement Method for Mobile Terminal Antennas at Lower UHF Band," *in Proceedings of the 5th European Conference on Antennas and Propagation (EuCAP 2011)*, Rome, Italy, pp. 1307–1311, 11–15 April 2011.

IV J. Ilvonen, O. Kivekäs, J. Holopainen, R. Valkonen, K. Rasilainen, and P. Vainikainen, "Mobile Terminal Antenna Performance With the User's Hand: Effect of Antenna Dimensioning and Location," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 772–775, 2011.

V J. Ilvonen, R. Valkonen, O. Kivekäs, P. Li, and P. Vainikainen, "Antenna Shielding Method Reducing Interaction Between User and Mobile Terminal Antenna," *Electronics Letters*, vol. 47, no. 16, pp. 896–897, August 2011.

VI J. Ilvonen, R. Valkonen, J. Holopainen, O. Kivekäs, and P. Vainikainen, "Reducing the Interaction Between User and Mobile Terminal Antenna Based on Antenna Shielding," *in Proceedings of the 6th European Conference on Antennas and Propagation (EuCAP 2012)*, Prague, Czech Republic, pp. 1889–1893, 26–30 March 2012.

VII J. Ilvonen, J. Holopainen, O. Kivekäs, R. Valkonen, C. Icheln, and P. Vainikainen, "Balanced Antenna Structures of Mobile Terminals," *in Proceedings of the 4th European Conference on Antennas and Propagation (EuCAP 2010)*, Barcelona, Spain, 5 pages, 12–16 April 2010.

VIII J. Holopainen, J. Ilvonen, O. Kivekäs, R. Valkonen, C. Icheln, and P. Vainikainen, "Near-Field Control of Handset Antennas Based on Inverted-Top Wavetraps: Focus on Hearing-Aid Compatibility," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 592–595, 2009.

Author's Contribution

Publication I: "Design Strategy for 4G Handset Antennas and a Multiband Hybrid Antenna"

The author had the main responsibility for developing the idea and content for the paper. Dr. Risto Valkonen and Dr. Jari Holopainen assisted in writing the paper. Prof. Ville Viikari supervised the work.

Publication II: "Multiband Frequency Reconfigurable 4G Handset Antenna with MIMO Capability"

The author had the main responsibility for developing the idea and content for the paper. Dr. Risto Valkonen and Dr. Jari Holopainen assisted in writing the paper. Prof. Ville Viikari supervised the work.

Publication III: "Isolation Improvement Method for Mobile Terminal Antennas at Lower UHF Band"

The author had the main responsibility for developing the idea and content for the paper. Dr. Azremi Abdullah Al-Hadi participated in analyzing the results. Dr. Outi Kivekäs instructed and Prof. Pertti Vainikainen supervised the work.

Publication IV: "Mobile Terminal Antenna Performance With the User's Hand: Effect of Antenna Dimensioning and Location"

The work was mainly done by the author. The author had the main responsibility for developing the idea. The author carried out the simulations and was responsible for writing the publication. Dr. Outi Kivekäs participated in the development of the idea and in writing the paper. Mr. Kimmo Rasilainen helped with the simulations. Dr. Outi Kivekäs instructed and Prof. Pertti Vainikainen supervised the work.

Publication V: "Antenna Shielding Method Reducing Interaction Between User and Mobile Terminal Antenna"

The antenna shielding idea is based on the joint idea of this author and Dr. Risto Valkonen. The author had a leading role for developing the idea, writing the publication and performing the simulations. Dr. Risto Valkonen participated in writing the paper and analyzing the results. Dr. Outi Kivekäs instructed and Prof. Pertti Vainikainen supervised the work.

Publication VI: "Reducing the Interaction Between User and Mobile Terminal Antenna Based on Antenna Shielding"

The work was mainly done by the author. The idea for the antenna shielding is presented in [V]. The author performed the simulations, design and fabrication of the prototype and measurements. Dr. Jari Holopainen instructed and Prof. Pertti Vainikainen supervised the work.

Publication VII: "Balanced Antenna Structures of Mobile Terminals"

The work was mainly done by the author. The author had the main responsibility for developing the idea. The author carried out the simulations and was responsible for writing the publication. Dr. Jari Holopainen participated in the development of the idea and worked as the instructor. Prof. Pertti Vainikainen supervised the work.

Publication VIII: "Near-Field Control of Handset Antennas Based on Inverted-Top Wavetraps: Focus on Hearing-Aid Compatibility"

This is the result of collaborative work. The idea was found by the author together with Dr. Jari Holopainen. Dr. Jari Holopainen had a leading role in writing the paper. The author carried out the simulations and participated in analyzing the results. Dr. Outi Kivekäs instructed and

Prof. Pertti Vainikainen supervised the work.

List of abbreviations

4G	4th generation mobile networks
5G	5th generation mobile networks
ANSI	American National Standards Institute
BBB	Blood-Brain Barrier
BT	Bluetooth
BUB	Combination of balanced and unbalanced antennas
CAD	Computer Aided Design
CCE	Capacitive Coupling Element
CDMA	Code-Division Multiple-Access
CLF	Conductance Loss Factor
CMOS	Complementary Metal Oxide Semiconductor
DTC	Digitally Tunable Capacitor
E-GSM	Extended GSM
EMC	Electromagnetic Compatibility
FCC	Federal Communications Commission
FDD	Frequency-Division Duplexing
FDTD	Finite-Difference Time-Domain
FET	Field-Effect Transistor
GaAs	Gallium Arsenide
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HAC	Hearing-Aid Compatibility
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
IFA	Inverted-F Antenna
ILA	Inverted-L Antenna
LTE	Long-Term Evolution communication system
LTE-A	LTE Advanced

MEG	Mean Effective Gain
MEMS	Microelectromechanical Systems
MIMO	Multiple-Input Multiple-Output
MoM	Method of Moments
MRC	Maximal Ratio Combining
NFC	Near-Field Communication
PCB	Printed Circuit Board
PEC	Perfect Electric Conductor
PIFA	Planar Inverted-F Antenna
QoS	Quality of Service
RAMS	Rapid Antenna Measurement System
RDF	Radio Direction Finding
RF	Radio Frequency
RHCP	Right-Hand Circular Polarization
RMS	Root Mean Square
Rx	Receiver
SAM	Specific Anthropomorphic Mannequin
SAR	Specific Absorption Rate
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
SPLSR	SAR to Peak Location Separation Ratio
TDMA	Time-Division Multiple-Access
TDD	Time-Division Duplexing
Tx	Transmitter
UHF	Ultra High Frequency band (300 - 3000 MHz)
UMTS	Universal Mobile Telephone System
VNA	Vector Network Analyzer
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

List of symbols

a	radius of a sphere enclosing an antenna
C	capacitance / capacitor
D	separation between SAR hotspots
DG	diversity gain
$\mathbf{E}$	electric field vector
E	electric field strength
EDG	effective diversity gain
$e_{\mathrm{rad,i}}$	total embedded radiation efficiency
f	frequency
f_{r}	resonant frequency
G_e	total conductance
G_{L}	radiation conductance
H	magnetic field strength
$\mathbf{J}$	current density vector
J	current density
$\jmath$	imaginary unit
k_0	wave number in free space
L	inductance / inductor
L_{P}	total resistive losses
L_{tot}	total losses
MEG	mean effective gain
m_h	mean elevation angle of horizontally polarized wave distribution
m_v	mean elevation angle of vertically polarized wave distribution
P_{loss}	absorption loss
P_{rad}	radiated power
Q	quality factor
Q_0	unloaded quality factor
Q_{rad}	radiation quality factor

Q_{Z}	quality factor calculated from input impedance
R	resistance / resistor
R_{L}	resistance of antenna
S_{11}	reflection coefficient
V	volume
XPR	cross-polarization ratio
Z_0	characteristic impedance
ϵ_0	permittivity in free space
ϵ_{r}	relative permittivity
$\epsilon_{\mathrm{r}}^{'}$	real part of relative permittivity
$\epsilon_{\mathrm{r}}^{''}$	imaginary part of relative permittivity
η	efficiency
η_{DTC}	efficiency of DTC component
η_{isol}	isolation efficiency
η_{m}	matching efficiency
η_{rad}	radiation efficiency
η_{tot}	total efficiency
$\tilde{\eta}_{mux}$	spatial multiplexing efficiency
λ	wavelength
λ_0	wavelength in free space
μ_0	permeability
ρ_{d}	density of tissue
ρ_{e}	envelope correlation coefficient
σ	conductivity
σ_{eff}	effective conductivity
σ_{h}	standard deviation of horizontally polarized wave distribution
σ_{v}	standard deviation of vertically polarized wave distribution
φ	phase of signal
ω	angular frequency
ω_{r}	angular resonant frequency

1. Introduction

1.1 Background

In the early 2000s, the main trends in mobile handset antenna development were miniaturization of the internal antenna structure and implementation of multi-frequency functionality. At about the same time, the standardized safety limits on the radio frequency exposure (SAR, specific absorption rate) were introduced [1]. It was also observed that in order to have robust antenna performance, the effect of the user cannot be neglected [2]. Despite this fact antennas were and still often are designed for free space, neglecting the effect of the user. Currently, devices tend to become larger mainly due to changes in ways of using mobile handsets; Internet browsing, near field communication (NFC), and positioning services are gaining popularity. Consequently, there is a need to increase the number of radios and antennas in handsets (see Figure 1.1) [3].

The number of antennas in small mobile devices has been continuously increasing along with the frequency band allocated for cellular use, while the volume reserved for the antennas has remained the same or even reduced. As a consequence, antennas easily become inefficient, thereby

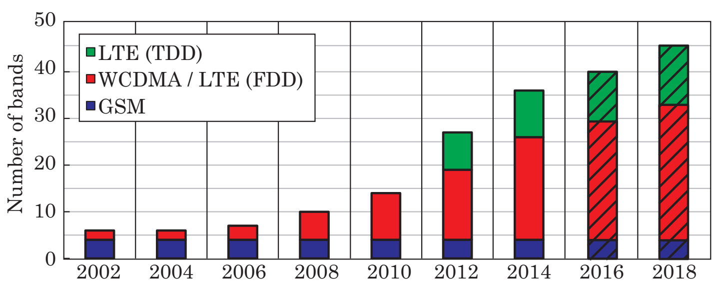


Figure 1.1. Evolution of cellular RF bands [4, 5].

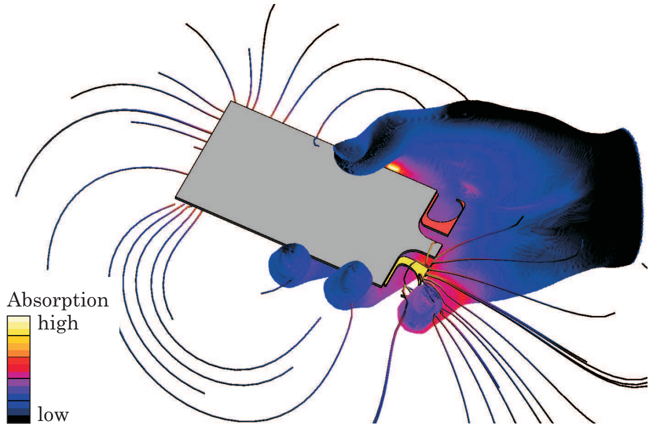


Figure 1.2. Distribution of absorption losses in hand and electric field flux at 900 MHz.

significantly lowering the achievable data rate and coverage. One possible solution to this challenge is to use small, frequency reconfigurable antennas to instantaneously cover only a part of the used band(s) [II], [6–10]. The feasibility of this approach has significantly increased due to recent developments in Complementary Metal Oxide Semiconductor (CMOS) and MicroElectroMechanical Systems (MEMS) technologies [11]. In addition to the increased number of antennas and mutual coupling issues, different ways of holding a handset and different hand grips have to be taken into account in order to ensure efficient antenna operation. Thus, there are plenty of new challenges and increased demands set for handset antennas.

The most demanding task in handset antenna design is to create small enough and realizable antennas which operate at multiple systems, have sufficient operational bandwidth, high radiation efficiency, and still can fulfill the requirements such as SAR and hearing-aid compatibility (HAC). Additionally, the antennas should perform well in the vicinity of the user (see Figure 1.2). Unfortunately, an antenna designer must make trade-offs between different antenna properties, as improving one property will deteriorate others [IV], [12,13]. Hence, it is difficult to develop an antenna element that will work well in all environments and devices.

1.2 Objective of the work

The general objective of this thesis is to investigate and develop environment insensitive handset antennas which are tolerant to environmental changes caused for instance by the user's body. Design principles and certain antenna implementations are given to achieve the objective. Another goal is to reduce the power absorbed by the user, meaning that the electromagnetic radiation emitted by the handset is directed away from the user and towards the targeted application. The thesis introduces novel techniques and design rules that can be used when designing antennas for future handsets. Fundamental properties of antennas have not been discussed in detail in this thesis and can be found, for example in [14–17].

1.3 Contents and organization of the thesis

This thesis consists of a summary and eight publications [I-VIII]. This summary is organized as follows. Chapter 2 focuses on the development of single- and multi-element antenna solutions for future mobile devices. In addition, design principles are introduced [I,II,III]. In Chapter 3, different challenges of handset antennas in the vicinity of the user are discussed [I,II,IV]. Furthermore, different methods to reduce the electromagnetic interaction between the user and a handset antenna are studied in Chapter 4 [II,V,VI,VII,VIII].

1.4 Scientific merits

This thesis presents a number of novel scientific results that can be used to develop multiband and environment insensitive handset antennas. The presented antenna designs have a very good performance in terms of antenna volume, bandwidth and efficiency exhibiting state-of-the-art performance in the field of handset antennas. The highlights of the thesis are:

1) A novel design strategy combining a non-resonant and a resonant antenna. The antenna operates with better than 50% efficiency across the frequencies of 698–2900 MHz and 3250–3600 MHz. This provides a very simple and easy method to design an LTE-A compliant antenna structure with a good performance [I].

2) A novel, independently frequency reconfigurable MIMO handset antenna. The antenna operates with an efficiency better than 49% across the frequencies of 698–960 MHz and better than 56% across the frequencies of 1430–2690 MHz. A new way of analyzing the suitability of the antenna geometry for frequency tuning is introduced [II].

3) A novel method to improve the isolation between antenna elements by using a combination of balanced and unbalanced antennas. The proposed structure can achieve up to 100 dB port-to-port isolation [III].

4) A systematic study of how small changes in the dimensions and locations of handset antennas affect the interaction between the antenna and the user's hand [IV].

5) A novel method to decrease the effect of the hand and head by using antenna shielding. The proposed structure can improve the total efficiency with hand and head by 5 dB, and decrease the SAR in the head by 81% at 900 MHz [V, VI].

6) The first analysis of feasibility of balanced antenna structures in mobile devices. One result of the analysis is that electromagnetic interaction between the antenna and the user can in some cases be decreased by using a balanced antenna instead of an unbalanced one. However, the use of balanced antennas is typically limited to higher UHF frequencies, above 2 GHz [VII].

2. Novel single- and multi-element handset antennas

Typically, the predetermined location and available volume for antennas in a mobile device set strict limitations for mobile antenna design [12,18]. Traditionally, the antenna element has been located in the top part of the device [2,19], and it was typically placed on the chassis [or printed circuit board (PCB)] without a ground clearance, as can be seen in Figure 2.1. This kind of design is also called an on-ground antenna, and it works as a shielding that weakens the E-field at the head side [V]. On the other hand, it increases the quality factor (Q), thereby decreasing the obtainable impedance bandwidth. The increase of the required frequency bands and consumers' demand toward ever slimmer devices has led to a typical solution in which the main antennas are located at the bottom part of the device in current handsets, as shown in Figure 2.2. A slim handset antenna covering the required frequency bands has typically a relatively large ground clearance of 10–15 mm. This design is known as an off-ground antenna, and it would result in extremely high SAR and HAC values if the element were placed at the top part of the device [I], [18,20–23]. An additional challenge is the change in performance when the user is located in close vicinity.

This chapter introduces the novel antenna structures that are developed in this thesis. Section 2.1 introduces and gives justifications for a non-

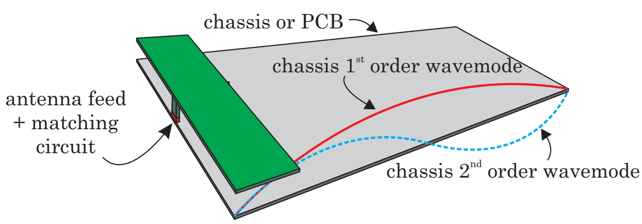


Figure 2.1. Generic capacitive coupling element (CCE) mounted on the chassis, with two principal current distributions of the lowest order chassis wavemodes.

(a)

#	Mode	Bands	Frequency range (MHz)
1.	**Antenna 1** *MIMO Rx / Diversity*	850 (Band 20)	791 – 862
		900 (Band 8)	880 – 960
		2500 (Band 7)	2510 – 2690
2.	**GPS**	GPS, Glonass, BeiDou	1559 – 1607
3.	**WLAN & BT**	2450	2402 – 2480
		5000	5150 – 5825
4.	**Antenna 2** *Main*	GSM850	824 – 849
		GSM900	880 – 960
		GSM1800	1710 – 1880
		GSM1900	1850 – 1990
		850 (Band 20)	791 – 862
		850 (Band 5)	824 – 894
		1800 (Band 3)	1710 – 1880
		1900 (Band 2)	1850 – 1990
		2100 (Band 1)	1920 – 2170
5.	**Antenna 3** *Main*	900 (Band 8)	880 – 960
		2500 (Band 7)	2510 – 2690
	Diversity	1800 (Band 3)	1710 – 1880
		2100 (Band 1)	1920 – 2170

(b)

Figure 2.2. (a) Internal antenna locations of *Nokia Lumia 930*[1]. (b) Operating frequencies of *Nokia Lumia 930*.

resonant-type antenna. The research methods used in this thesis are introduced in Section 2.2. Section 2.3 discusses the benefits and drawbacks of broadband handset antennas and introduces a novel hybrid antenna for multi-standard handsets [I]. Section 2.4 discusses different frequency tuning technologies and introduces a new way of analyzing the suitability of the antenna geometry for frequency tuning [II]. In Section 2.5, a novel method to improve the isolation between antenna elements is shown.

2.1 Background of non-resonant antennas

The PCB or chassis of the handset is used as a radiator and the antenna element creates the antenna resonance, possibly together with a matching circuit. Especially at the low-band (698–960 MHz), a significant portion of the power is radiated by the chassis [24]. The contribution of the chassis to the total radiation is between 90 and 95% at 900 MHz and between 30 and 70% at 2000 MHz with the studied capacitive coupling element (CCE) antennas [IV], [25].

The capacitive coupling element (CCE) based antenna structures, originally introduced in [24, 26] (see Figure 2.1), are mostly used in this thesis to investigate and demonstrate the interaction between the antenna and the user. The non-self-resonant type CCE antennas are especially suit-

[1]Image source: http://www.nokia.com/gb-en/phones/phone/lumia930/

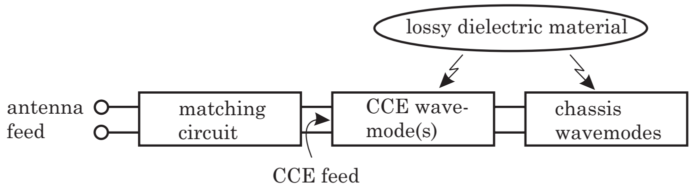


Figure 2.3. Circuit blocks of the equivalent circuit model with lossy dielectric loading (such as the user) [25].

able for this kind of study due to the following reasons: *a*) the CCE can be tuned with an external matching circuit to have a resonance at almost any frequency, *b*) the impedance bandwidth can be enhanced by using a matching circuit with multiple resonances, *c*) a low inherent selectivity makes the CCE a promising antenna to be used in frequency reconfigurable systems, *d*) the geometry of the antenna element can be very simple, *e*) the geometry of the antenna element is not dependent on the operating frequency and thus investigating the user-originated losses is straightforward, and *f*) the contribution of the dielectric loading caused by the user is fairly evenly distributed over the CCE due to the lack of fine geometrical details [I], [27–30].

In addition to the above-mentioned features, CCE antennas can be used to analyze the properties of the chassis wavemodes with the user. This is because the CCE is inherently non-self-resonant and it can thus be seen as a ”transparent” transformer between the matching circuit and the chassis (see Figure 2.3) [25, 31].

2.2 Research methods

The results and conclusions presented in this thesis are based on simulations and measurements. The consistency between the simulated and measured results is excellent, which corresponds well with the previous research made by other researchers [32–37].

A typical feature of handset antennas is that they have low directivity, which poses challenges for antenna measurements. For example, a simple and approximate directivity/gain method is not valid as the antenna does not have a strong main lobe, and thus one has to measure 3D radiation pattern in order to determine the far-field properties such as realized gain or polarization [38]. In addition, it is difficult to position the RF feed cable in such a way that it does not affect the radiation pattern or the electrical

(a) (b) (c)

Figure 2.4. Measurement set-up (a) in RAMS including a user, (b) in small anechoic chamber including a phantom hand, and (c) in absorber box.

length of the chassis [39, 40].

In this thesis, the pattern measurements were carried out using two different in-house 3D measurements systems with a capability of measuring complex fields (see Figure 2.4): *a*) Rapid Antenna Measurement System (RAMS) that is capable of measuring the effect of a real user [41, 42], and *b*) a small anechoic chamber [43, 44]. All impedance measurements are done with the help of an "absorber box" in order to avoid reflections from the surroundings [38, 45]. Moreover, several ferrite bead chokes are used to prevent current flow on the surface of the feed cable. The uncertainty of the efficiency measurement is about ± 0.5 dB, and it is mainly due to the limited measurement distance (ca. 1–1.4 m), the performance of the RF absorbers, the finite number of measurement points used, and reflections in the measurement cables.

The simulations are performed using four different types of commercial EM and circuit simulators: *a*) an FDTD-based EM-simulator SEMCAD X by SPEAG [46], *b*) a Method of Moments (MoM)-based simulator IE3D by Mentor Graphics [47], *c*) a circuit simulator AWR Design Environment [48], and *d*) an antenna analysis simulator Optenni Lab [49].

2.3 Broadband handset antenna

Today's mobile handsets have to cover a wide range of different frequencies, as already shown in Figure 2.2. Beyond these, there are also many other frequency bands, which the example *Nokia Lumia 930* phone does not use [50]. However, the reason why all available frequency bands are not included is probably that the manufacturers have to make compromises between the size and radiation properties of the handset and the frequency bands required by the network operators in a particular geographical location. It is very challenging to design a handset antenna that can cover all required frequency bands while having a very small antenna volume and good radiation properties. Different handset antenna techniques have been proposed in previous years to achieve this goal, such as self-resonant type [8, 22, 23, 37, 51–55] and nonself-resonant type [II], [18, 26, 36, 56, 57] antennas. Self-resonant antennas are widely used and well-performing, but as the number of frequency bands increases, the geometry of the antenna gets very complex [22]. In comparison, the antenna geometry can be very simple with non-self-resonant antennas but the matching circuit might be challenging to design [56, 58, 59]. Typically, the reduction of the antenna volume results in restricted number of frequency bands covered and/or reduced total efficiency [36]. In [I], a novel hybrid antenna that combines an inherently non-resonant capacitive coupling element (CCE) [26] and a self-resonant inverted-L antenna (ILA) [60] is introduced. The proposed antenna combines the advantages of both designs, thus having state-of-the-art performance in terms of antenna volume, bandwidth and efficiency.

2.3.1 Hybrid antenna

A design strategy for a novel 4G handset antenna is introduced in [I]. Based on the design process, one possible multi-antenna implementation including the hybrid as a main antenna and a traditional ILA as an auxiliary antenna, is shown in Figure 2.5. The operation of the hybrid antenna is based on using a low-band matching circuit with a high-pass type frequency response enabling the use of the same antenna element as self-resonant at higher frequencies. The antenna is designed by taking the matching capabilities into account, and thus only two matching components are needed. Further details on this antenna can be found in [I].

The main antenna operates with better than -3 dB (50%) efficiency at the frequencies of 698–2900 MHz and 3250–3600 MHz, as can be seen in Figure 2.6[2]. The auxiliary antenna is designed to operate at the frequencies of 2110–3680 MHz, and better than 10 dB of isolation is achieved between the antennas.

This design does not include a low-band auxiliary antenna. This is because the low-band auxiliary antenna cannot be located within the volume of the main antenna due to the high electric field distribution between the

[2]The measurements were performed without the auxiliary antenna.

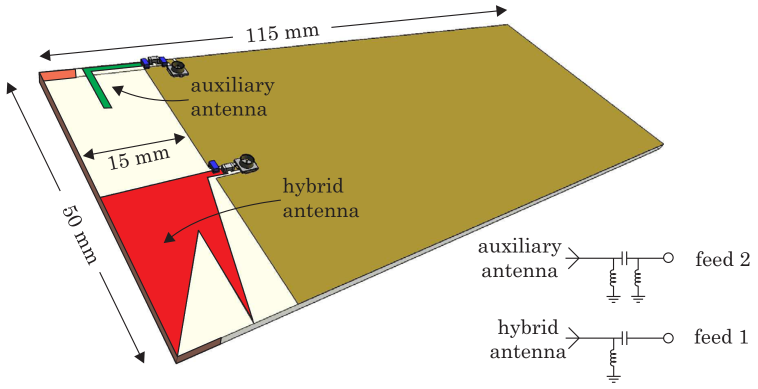


Figure 2.5. Schematic view of the hybrid antenna structure with main and auxiliary antennas.

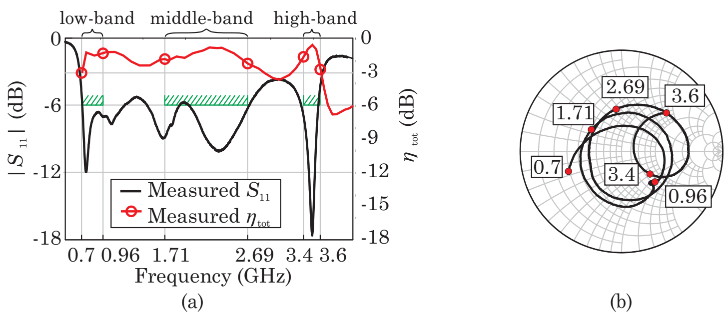


Figure 2.6. (a) Measured impedance matching and total efficiency of the prototype antenna in free space. (b) Measured input impedance of the prototype antenna in free space. The measurements are made without the auxiliary antenna.

main antenna and the chassis. However, the low-band auxiliary antenna can be located, for example on the long side of the chassis [61], as is done in the *Nokia Lumia 920* phone.

The superiority of the hybrid antenna over traditional antenna designs is demonstrated by the fact that the good characteristics are achieved by using a very simple antenna geometry and a matching circuit with only two lumped components. However, this can also be a drawback, as will be shown next. The bandwidth requirement at the low-band defines the required antenna volume. In principle, the antenna volume might be decreased by using multi-resonant matching circuits discussed in [58, 62, 63]. However, the simple and effective multi-resonant circuits presented in [58] do not operate as a high-pass type matching circuit at higher frequencies, thus removing the benefit of the simple matching circuit in the hybrid antenna.

2.4 Frequency reconfigurable handset antenna

As an alternative to broadband matching, broad virtual impedance bandwidths can be implemented with impedance tuners and/or frequency reconfigurable matching circuits that can be used, for example, to decrease the required antenna volume and to compensate the user-originated detuning losses, as shown in [II]. The required instantaneous impedance bandwidth together with a maximum useful antenna radiation Q limits the possible reduction of the antenna volume. The antenna Q will increase as the volume of the antenna decreases, and impedance bandwidth is inversely proportional to Q [64]. In addition, high-Q antennas are inherently more sensitive, for example, to metal and matching circuit losses. Hence, the maximum usable antenna Q is typically considered to be between 50 and 100 [10, 65, 66].

For example in LTE systems with full-duplex scheme, the instantaneous bandwidth requirement at the low-band is between 48 and 80 MHz[3], covering both the receiver (Rx) and transmitter (Tx) bands. This corresponds roughly to a Q of 15–20, which is well below the threshold (50–100) that causes an increase in metal losses. In [67], a novel technique to split the frequency bands of Rx and Tx between separate antennas is proposed, hence narrowing the required instantaneous bandwidth. This technique simplifies the RF front-end design since duplex filters are not needed and the instantaneous bandwidth requirement of the antenna is more than halved, thus making it possible to use antenna elements having a Q of even 50. This brings the antenna Q close to the upper Q limit and additional attention should be paid toward, for example, metal and component losses. This method also increases the number of antennas, making it more complicated to design handsets with MIMO capability.

2.4.1 Frequency tuning techniques

Many different frequency reconfigurable handset antennas have been proposed, for example, in [9, 20, 68–74]. Some of them are based on the idea of combining a self-resonant antenna and a tunable capacitor [69, 71, 73, 74], or a multi-state switch having different matching schemes [72]. Also, structures using nonself-resonant elements are presented [9, 20, 68, 70]. The use of nonself-resonant elements [26, 29] is justified due to their low

[3] LTE band 12: 698–746 MHz, LTE band 14: 758–798 MHz, LTE band 5: 824–894 MHz and LTE band 8: 880–960 MHz.

inherent selectivity, which makes their frequency tunability more prominent compared to self-resonant elements [9, 20]. Furthermore, nonself-resonant antennas require the use of matching circuits anyway, meaning that tunability will not add much to the complexity of the matching circuit.

A varactor diode is traditionally used as a tunable capacitor in frequency reconfigurable systems [70, 71, 73]. The capacitance of the varactor can be varied by changing the voltage applied across its terminals. However, a drawback with the varactor is that its inherent nonlinearity causes distortion. Alternatively, CMOS- or MEMS-based digitally tunable capacitors can be used. Distortion of such digital components is potentially much lower than that of a varactor. MEMS, in particular, is ideally distortionless. In addition, RF MEMS components have some overwhelming advantages over traditional semiconductor components [75, 76]. They can be used to build RF circuits with very low power consumption, size and loss resistance ($Q > 100$–600). Some time ago, the drawbacks of RF MEMS technology were limited lifetime, relatively bulky components, and poor availability. At the moment, there are several commercial companies, such as [77, 78], that are selling RF MEMS switches and tuners. In addition, lifetimes of MEMS are also reported to be sufficient for commercial devices [79]. In this work, CMOS- and MEMS-based DTCs are used to implement novel tunable antennas for mobile handsets.

2.4.2 Loss analysis of frequency reconfigurable handset antennas

The antenna Q is the traditional way of assessing the radiation efficiency performance of handset antennas. The idea is that the antenna Q together with the component losses[4] determines the efficiency of the antenna system. In [80], the concept of bandwidth potential [26, 30, 81] was used to analyze the efficiency of tunable antenna elements. It was concluded that tunable antennas with a relatively high Q are sensitive to matching component losses.

To the author's knowledge, the first analysis of the suitability of a particular antenna geometry for frequency tuning is introduced in [II]. It is shown that for efficient performance of the tuning circuit, the antenna impedance should be chosen properly. The studied geometries are shown in Figure 2.7 (a). The studied antennas are inherently capacitive across

[4] $\eta_{\text{ant}} = Q_{\text{comp}}/(Q_{\text{comp}} + Q_{\text{ant}})$, in which the antenna itself is assumed lossless.

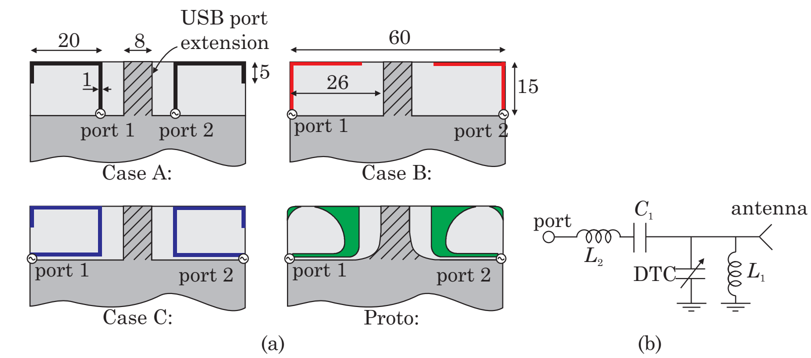


Figure 2.7. (a) Studied antenna geometries. Cases A-C are planar, whereas Proto has a height of 5 mm. (b) Circuit schematic of the tunable matching circuit.

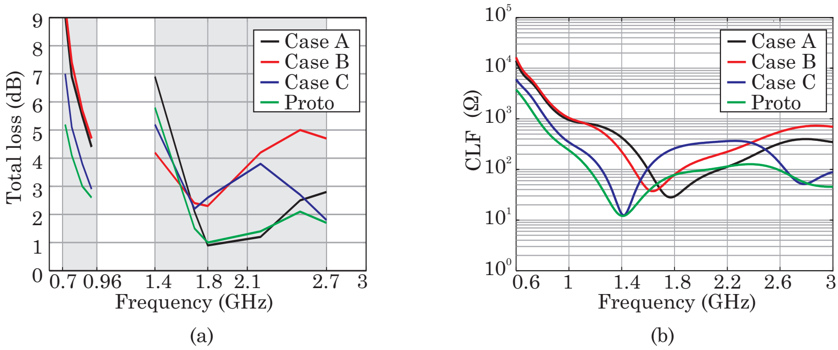


Figure 2.8. (a) Simulated total loss with CMOS-based DTC. (b) CLF of the studied antenna structures.

most of the LTE-A bands, and thus the frequency tuning is implemented by using a CMOS-based digitally tunable capacitor (DTC) [82] together with three fixed lumped components, as shown in Figure 2.7 (b). The used matching circuit combines the performance of low-pass and high-pass resonators and the analysis of such circuits is presented in [58].

Typically, a large antenna Q results in high resistive losses of the antenna structure and matching circuit. However, this method does not necessarily lead to the best antenna geometry for frequency reconfigurable antennas. The Q of Cases A, B and C is 23.8, 24.0, and 26.0, respectively, at 720 MHz. Although Case C has the highest Q of the three at the example frequency, it performs best in terms of total loss (L_{tot}) when the tuning circuit is employed, as shown in Figure 2.8 (a).

A numerical study on the losses of the matching circuit was performed in [II]. It revealed that the DTC and inductor L_1 [see Figure 2.7 (b)] dominate the total resistive losses at all frequencies and DTC states. Hence, the total resistive losses, can be approximated as

$$L_{\mathrm{P}} = 1 + G_{\mathrm{e}}/G_{\mathrm{L}} = 1 + \frac{R_{\mathrm{e}}}{R_{\mathrm{e}}^2 + X_{\mathrm{e}}^2} \frac{R_{\mathrm{L}}^2 + X_{\mathrm{L}}^2}{R_{\mathrm{L}}} \tag{2.1}$$

where G_{e} is the total conductance of the DTC and L_1, and G_{L} is the radiation conductance of the antenna. In the low-band, G_{e} is varying relatively little across the whole frequency band, and thus its effect can be neglected. Finally, the efficiency of the matching circuit is inversely proportional to the radiation conductance of the antenna. The Conductance Loss Factor (CLF) for the most promising antenna geometry can be derived from (2.1) and can be expressed as

$$\mathrm{CLF} = \frac{1}{G_{\mathrm{L}}} = \frac{R_{\mathrm{L}}^2 + X_{\mathrm{L}}^2}{R_{\mathrm{L}}}. \tag{2.2}$$

In general, a better tuning circuit efficiency is obtained with a lower CLF. The CLF corresponds well with the L_{tot} results shown in Figure 2.8 (a), especially at the low-band. At the high-band, the comparison is not as straightforward because of the matching losses included in the L_{tot}.

The loss study revealed that the best total efficiency is achieved when the radiation conductance of the antenna element remains at a reasonable level across the whole band. Thus, Case C is the best candidate to be studied further. However, the performance of Case C near 2.2 GHz is limited, as shown in Figure 2.8 (a). This is mainly due to a large series inductance caused by the long and thin feeding strip (length 35 mm). This can be avoided by using a curved feed [II] that decreases the effective series inductance and keeps the effective parallel capacitance suitable. One possible way to reduce feed inductance through shape optimization is shown in Figure 2.7 (Proto).

2.4.3 Tunable prototype antenna

In [II], a more comprehensive analysis of the thought process that lead to the prototype antenna is given. Figure 2.9 (a) shows the schematic view of the antenna structure. The antenna elements are located symmetrically with respect to the long axis of the chassis. This simplifies the implementation of the matching circuit with a CMOS-based DTC. The state of the DTC is varied with a laptop connected to the prototype by using a serial interface. A battery is used to maintain the state of the DTCs to avoid the extra cable during measurements. The measurements were made only for the CMOS-based DTC because of limited availability of the MEMS-based DTC at that time.

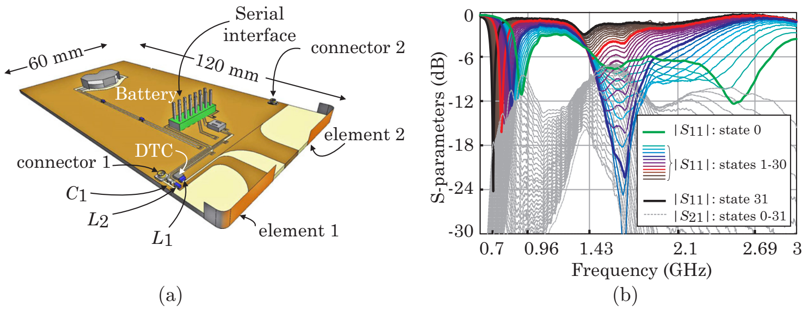


Figure 2.9. (a) Schematic view of the MIMO antenna structure. (b) Measured S-parameters with CMOS-based DTC in free space. Both elements are operating at the same frequency.

The measured impedance results of the prototype are shown in Figure 2.9 (b). In order to mimic the worst case scenario, both antenna elements are operating at the same frequency. It can be seen that the antenna can cover most of the LTE-A bands with reasonable isolation between the antenna elements. The antenna elements can be tuned to operate at different frequency bands or to compensate the user-originated impedance detuning.

2.4.4 Comparison between MEMS- and CMOS-based DTC

The distribution of the matching circuit losses is further analyzed in Table 2.1 which compares the CMOS- and MEMS-based DTCs at different frequencies. The total efficiency with the WiSpry WS1050 DTC is only simulated because of limited availability of the components at the time of the measurements. The isolation efficiency (η_{isol}) includes the coupling losses between the antennas and the component losses of port 2. The matching (η_{m}) and series component efficiencies are negligible. As can be seen in Table 2.1, a significant portion of the losses is caused by the shunt inductor (L_1) in addition to those of the DTC. The purpose of L_1 is to tune the antenna to the correct frequency band, meaning that a relatively large current flows through the component (especially at the low-band). Nevertheless, the components have to be placed this way to establish the desired tuning range. The losses of Peregrine's CMOS-based DTC are very high (2.9 dB) at the low-band, as already suggested by its low Q. On the other hand, the losses of WiSpry's MEMS-based DTC are significantly smaller (less than 0.5 dB).

Table 2.1. Loss study of *Proto*. The efficiencies are calculated when element 1 is transmitting and element 2 is connected to a 50-Ω termination. The elements are working at the same frequency.

		Simulated				Measured
DTC model	freq (MHz)	η_{DTC} (dB)	η_{L1} (dB)	η_{isol} (dB)	η_{tot} (dB)	η_{tot} (dB)
Peregrine	720	-2.9	-2.1	-0.2	-5.2	-5.2
PE64904	770	-1.9	-1.6	-0.5	-4.1	-4.2
(CMOS)	850	-0.9	-1.0	-0.9	-3.0	-3.7
[82]	920	-0.4	-0.7	-1.4	-2.6	-3.0
	1700	-0.1	-0.0	-0.6	-1.3	-1.9
	2000	-0.2	-0.1	-0.3	-1.0	-1.3
	2500	-0.5	-0.1	-0.4	-2.3	-2.4
WiSpry	720	-0.5	-1.8	-0.1	-2.4	N/A
WS1050	770	-0.3	-1.0	-0.4	-1.8	N/A
(MEMS)	850	-0.1	-0.6	-0.8	-1.4	N/A
[77]	920	-0.0	-0.4	-1.2	-1.8	N/A
	1700	-0.1	-0.1	-0.3	-1.4	N/A
	2000	-0.1	-0.1	-0.3	-0.7	N/A
	2500	-0.1	-0.1	-0.4	-1.5	N/A

2.5 Mutual coupling

The last part of this chapter discusses the mutual coupling between the antennas. If multiple antennas are mounted on the same chassis, there will inevitably be strong mutual coupling between them (especially below 1 GHz) because each antenna element has a strong coupling to the common chassis and are hence connected together. Even an optimized placement of the antenna elements or galvanic isolation will not give significant EM isolation improvement in that frequency band. High mutual coupling, i.e., low isolation between the antennas decreases the efficiency and might deteriorate the diversity properties [83]. Thus, high isolation is desired and the limit for sufficient isolation is generally considered to be at least 6–10 dB [23, 84, 85], which corresponds to an extra loss of 0.5–1.3 dB [$\mathrm{loss} = -10\log_{10}(1 - |S_{i,j}|^2)$].

A typical way to express the isolation between the antennas is to use scattering parameters [$\mathrm{isolation} = -20\log_{10}(|S_{i,j}|)$]. However, this method takes into account, for example, the matching losses, which makes comparing the isolation properties of different antenna structures difficult. A more useful method is to use the concept of electromagnetic (EM) isolation, which defines the isolation between antenna elements in a theoretical case where all elements are perfectly matched with lossless matching circuits [81]. For example, the measured isolation of the frequency tunable antenna presented in [II] was in the range of 8–18 dB and the simulated EM isolation was in the range of 5–6 dB at the low-band. A relatively large difference is mainly caused by the DTC losses and finite matching levels. Hence, it is difficult to compare the isolation properties of different antenna structures by using a ”traditional isolation”. Without using any isolation improvement techniques, the EM isolation is typically between 3 and 7 dB at the low-band, depending on the antenna locations.

Different isolation techniques have been investigated in many previous publications [84, 86–93]. However, most of these techniques are based on the resonance phenomenon and have thus inherently narrow bandwidth. In addition, at the lower UHF frequencies, resonance-based isolation structures can be impractically long to be used in mobile handsets. Other techniques are based, for example, on optimal antenna placement and/or combining different types of antennas.

A popular neutralization line technique to improve the isolation was introduced in [86]. The operating principle of the original neutralization line is to create an opposite coupling between the ports, and it is realized by linking two antennas by a suspended microstrip line having a certain length. The USB port extension, shown in Figure 2.10 (a), operates as a modified neutralization line as it provides two distinct current paths between the ports, thus causing an opposite coupling at certain frequencies. At the low-band, the EM isolation is improved by 2–3 dB compared to the case without the USB extension, but the EM isolation is simultaneously deteriorated at the high-band. Instead of using a simple and narrowband neutralization line, one can use a more complicated neutralization techniques presented, for example in [84, 85]. However, this technique can decrease the radiation efficiency if located in the vicinity of the radiating structures. For example, the tuning circuit losses of frequency reconfigurable antennas can be increased due to deteriorated impedance performance (e.g., increased reactance), as discussed earlier in Section 2.3.2

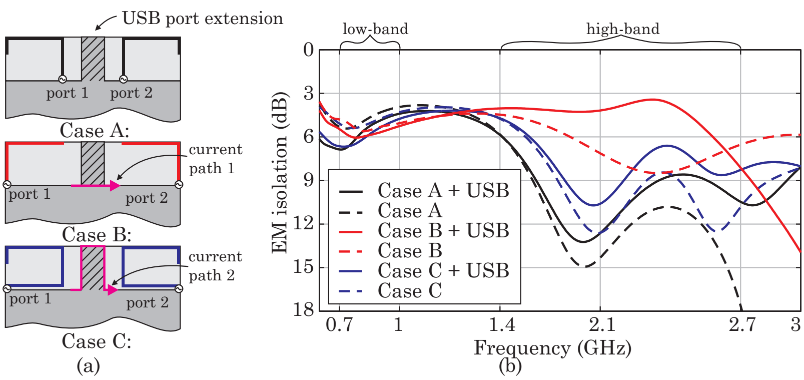


Figure 2.10. (a) Studied antenna geometries. (b) Simulated EM isolation between the antennas with and without the USB extension.

2.5.1 Feed location and antenna geometry

Next, the effect of the feed locations and antenna geometry on isolation performance is briefly discussed. The studied cases are shown in Figure 2.10 (a) and the exact antenna dimensions can be found in [II].

As shown in Figure 2.10 (b), the location of the feeds does not have a significant effect on the EM isolation, and neither does the antenna geometry at the low-band. However, the case is different at the high-band where the antenna geometry has a strong influence on the EM isolation performance. The poor isolation (with Case B) is due to the strong EM coupling of the closely positioned open ends. This result suggests that in order to have a good isolation performance, the open ends of the antennas should be pointing away from each other, as with Cases A and C. This information can be utilized to improve the inherent EM isolation of the handset antennas at higher frequencies.

2.5.2 Combination of balanced and unbalanced handset antennas

One solution to improve the isolation between the antennas is to use a combination of balanced and unbalanced antennas (BUB) [III]. The BUB antenna studied in this thesis consists of helix and CCE antennas located at opposite ends of the chassis, see Figure 2.11. The desired resonances in both antennas are achieved by using matching circuits. Two reference cases are investigated to obtain reliable evaluation of the proposed isolated antenna structure, see Figures 2.12 (b) and 2.12 (c).

The simulated port-to-port isolation between the antennas is up to 100 dB in the proposed BUB. The corresponding isolations for references #1 and #2 are 3.5 and 5.5 dB, respectively. The BUB structure has almost orthogonal dipole-type radiation patterns, as can be seen in Figure 2.12 (a).

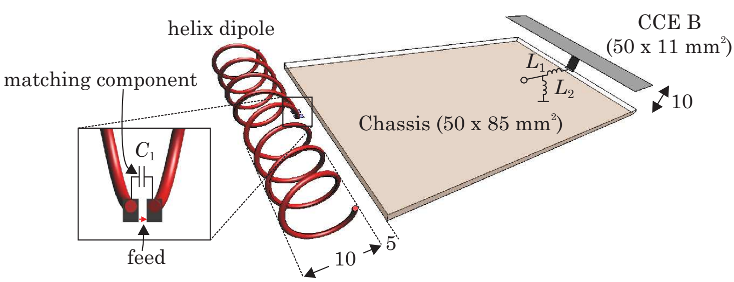


Figure 2.11. Antenna structure having CCE and helix antennas (BUB). Dimensions are in millimeters.

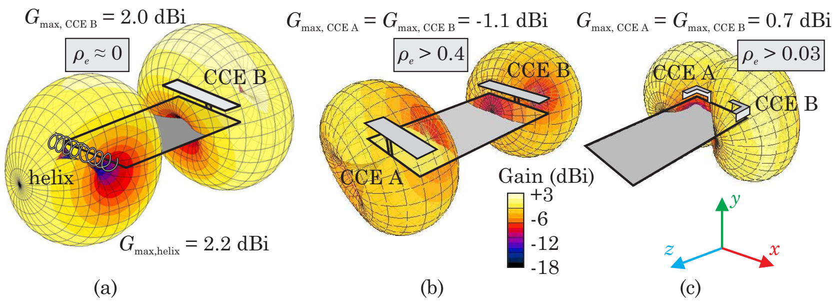


Figure 2.12. Simulated 3-D radiation properties of (a) the BUB, (b) reference #1, and (c) reference #2 structures in free space.

Table 2.2. Estimated diversity performance of the antennas in different propagation environments at 900 MHz. MEG_1 refers to the helix or CCE A and MEG_2 refers to CCE B.

Structure	isotropic				urban 1				urban 2			
	ρ_e	MEG_1 (dB)	MEG_2 (dB)	EDG (dB)	ρ_e	MEG_1 (dB)	MEG_2 (dB)	EDG (dB)	ρ_e	MEG_1 (dB)	MEG_2 (dB)	EDG (dB)
Ref. #1	0.406	-6.54	-6.54	7.12	0.787	-9.22	-5.88	3.46	0.817	-6.19	-4.26	4.19
Ref. #2	0.028	-4.70	-4.70	9.89	0.083	-6.41	-3.12	8.14	0.405	-3.88	-3.33	8.61
BUB	0.000	-3.28	-3.57	11.01	0.174	-3.56	-6.34	9.39	0.004	-5.26	-2.72	9.89

This is due to the fact that the antenna structures and thus their ”effective length vectors” are oriented perpendicularly to each other and because the balanced structures are well isolated from the chassis. Consequently, the envelope correlation (ρ_e) defined from the 3-D radiation patterns [94] predicts a high effective diversity gain (EDG) for the BUB antenna. The helix has also very low cross-polarization, which indicates extremely low coupling to the chassis wavemode. Reference #2 has also a very low ρ_e, meaning that a low ρ_e does not necessarily indicate high isolation.

The diversity performance of the antenna structure can be estimated by calculating the mean effective gain (MEG) [95] and the ρ_e [94] in different radio propagation environments. Good diversity performance necessitates low cross-correlation between the individual branches, otherwise deep fades in the branches will occur simultaneously decreasing the EDG. Also the mean powers available from both antenna branches should be equal to each other to avoid deterioration of the signal [96].

The proposed BUB outperforms the references by 1.1–6.2 dB margins, depending on the environment and structure under comparison. In real environments, the MEG imbalance of the BUB restricts the achievable EDG between 9.4 and 9.9 dB. Reference #2 performs almost equally well as the BUB in urban 2 environment due to a very low MEG imbalance.

In addition, it is good to note that the results of Table 2.2 are calculated at one frequency point (900 MHz) and since the helix is quite narrowband (2–3% at the 900-MHz frequency band, having a Q of 67–44), the corresponding MEGs are narrowband as well. Therefore, the frequency band where the EDG is valid is limited by the element that has the narrowest impedance bandwidth.

The idea of the BUB antenna can be used to improve the EM isolation between the antennas. In addition, the simulation results show that the proposed structures can achieve a good diversity performance in a real propagation environment. Therefore these structures can be used, for example, in MIMO systems to increase the data throughput [97] and the link coverage [98] without additional frequency bandwidth or transmit power. The drawback is that the achieved impedance bandwidth of the proposed BUB antenna is not large enough to cover the requirements at the low-band, thus requiring, for example, the use of frequency tuning. It is noted that it is very challenging to achieve an extremely high isolation (e.g. 100 dB) in practice. This is because of manufacturing tolerances, properties of realistic feed lines, effect of the user and so on. In addition, an isolation of 20–40 dB is probably enough for handset antennas in most cases.

Despite of excellent MIMO performance below 1 GHz, it can be concluded that the BUB antenna structures are best suited for upper UHF frequencies, above 2 GHz, where sufficient bandwidth is easier to achieve and the antenna can be relatively small in size. Thus, it is a promising structure to be used as a high-band MIMO/diversity antenna located at the top-part of the handset, see Figure 2.2. In addition, the BUB antennas can be used in applications that require an excellent electromagnetic isolation between the antennas and in improving the EDG in MIMO systems. Moreover, the BUB antennas might also be well-suited for radio direction finding (RDF) applications where at least three closely-packed, isolated antenna elements are needed [99].

3. Handset antennas in the vicinity of the user

Today's handset antennas utilize the chassis of the device as a radiator, facilitating good performance also below 1 GHz [24]. Therefore, the size of the handset on which the antenna is located and the location of the antenna relative to the chassis have a considerable effect on the handset antenna performance [I,II,IV], [21, 100, 101]. In addition, the effect of the user on the operation of the handset antenna has to be taken into account from two different perspectives. The human body can affect the operation of the antenna and vice versa.

The effect of the user on the impedance matching and radiation efficiency is discussed in Section 3.1. In Section 3.2, beneficial approaches and general guidelines for antenna designs with reduced sensitivity to the user's hand are given [IV]. The hand losses of narrow- and broadband antennas are discussed in Section 3.3 [I,II]. When multiple antennas are present, the analysis of the effect of the user becomes more complex when multiple antennas are present. These issues are considered in Section 3.4, in which different MIMO performance metrics are shown and explained. Finally in Section 3.5, the main disadvantages of the electromagnetic radiation of the handsets for the user are discussed.

3.1 User effect on impedance matching and radiation efficiency

An additional challenge for the design of handset antennas is the inevitable change of performance when the user is located in close vicinity to the device. In most cases, the effect of the user on the performance of the antenna is detrimental causing, for instance, a reduction of RF power, input impedance variation, and a change in the radiation pattern [II,IV,VII], [28, 87, 102–108]. Existing broad understanding of the head effect [12, 109–113], as well as the increasing use of data services direct

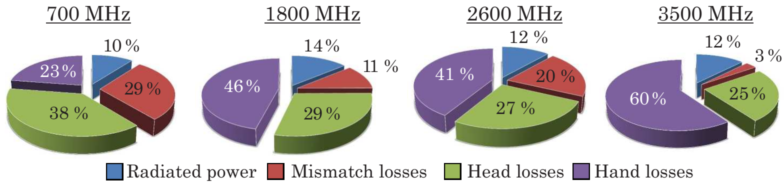


Figure 3.1. Distribution of the losses at different frequencies with bottom-located antenna.

the focus of research to studies on the effect of the hand. Small tolerances in the dielectric parameters or geometry of the hand and the head have a small impact on antenna performance, while the most important factor is the way the handset is held with respect to the antenna element [114–117]. The effect of the hand, especially the index finger with top-located antennas, or the little finger or palm with bottom-located antennas, has a significant effect on the antenna performance.

In [I], the user effect of a bottom-located antenna is studied. The absorption loss with the head alone is 1.7–7.3 dB, and in general, the losses decrease as the frequency increases. This is a consequence of the relatively large distance between the bottom-located antenna element and the head. At lower frequencies, the chassis is the main radiator, and the open end of the chassis (close to the ear) has strong electric fields causing high losses. The effect of the chassis will decrease as the frequency increases, and the radiation is concentrated close to the antenna element, thereby decreasing the head losses when the antenna element is bottom-located. Figure 3.1 shows an example distribution of the losses at different frequencies when both the hand and the head are considered. A few observations can be made as the frequency increases: *a*) the percentage of the radiated power remains almost unchanged, *b*) losses in the hand increase and those in the head decrease, and *c*) mismatch losses decrease. However, the behavior of the mismatch losses cannot be generalized for all antenna types and the distribution of the losses is dependent on the hand and head phantoms used.

Furthermore, it is very challenging to design an antenna having a robust performance considering statistical variations of possible different hand grips of the users [114]. In the multi-antenna case, the effect of the hand can degrade the data throughput due to significant mean effective gain (MEG) imbalance between different antenna branches [118]. On the other hand, in a few cases the user's hand can even improve the performance of lower UHF band antennas. This can occur below 1 GHz, for instance, when the hand is located at the opposite end of the chassis as the antenna element [31, 35, 119]. The improvement of the total efficiency in this particular case is due to the improved matching efficiency which more than compensates the reduction of the radiation efficiency.

The deterioration of the performance of the handset antenna located close to the human body is due to the fact that the human tissue consists of lossy dielectric material[1]. The lossy tissue in the reactive near fields of the antenna causes the problems discussed above. The performance degradation can be described as a change of the total antenna efficiency (η_{tot}) between the free space case and with the user. The total antenna efficiency is the product of radiation (η_{rad}) and matching (η_{m}) efficiencies.

The matching efficiency is defined as the ratio of the power accepted by the antenna to the power available at the antenna input [120]. Typically, the change of the resonant frequency of the antenna will decrease the η_{m}. Perturbation theory for a filled cavity [121] can be used to approximate the frequency detuning caused by the human body. The theory can be extended to handset antennas (with some limitations which will be discussed later) due to the fact that their operation is based on the resonant wavemodes of the antenna element and the chassis [24, 93, 122, 123] (see Figure 2.1). An approximation for the shift of the resonant frequency due to a change in permittivity (ε) can be obtained from the general perturbation formula [121]:

$$\frac{\omega-\omega_0}{\omega} \approx -\frac{\varepsilon-\varepsilon_0}{2\varepsilon}\frac{\int_V \mathbf{E}\cdot\mathbf{E}_0^* dV}{\int_V |E_0|^2\, dV}. \tag{3.1}$$

The subscript 0 refers to the free space case. The equation states that dielectric material (e.g., hand having $\varepsilon_r^{'}$ = 36.2 at 900 MHz) located within the reactive near fields will decrease the resonant frequency of the antenna, typically deteriorating the matching efficiency (η_{m}). However, this is valid only for a closed cavity and thus cannot directly be extended to handset antennas, which are a combination of antenna element(s) and a chassis, and consisting of several coupled wavemodes. Hence, some specific cases can be found where the resonant frequency of the antenna structure can slightly increase due to dielectric loading [31].

The radiation efficiency is defined as the ratio of the power radiated by the antenna to the power accepted by the antenna [120]. It means that the lossy dielectric material (tissue) close to the antenna decreases the

[1] $\varepsilon_r = \varepsilon_r^{'} - \jmath\sigma_{eff}/\omega\varepsilon_0$, where $\varepsilon_r^{'}$ is the real part of the relative permittivity, ε_0 is the permittivity of free space, and σ_{eff} is the effective conductivity.

η_{rad}. The loss power in the dielectric is [124]

$$P_{\text{loss}} = \frac{1}{2}\int_V \mathbf{J}\cdot\mathbf{E}^* dV = \frac{\rho}{2}\int_V |\mathbf{E}|^2\, dV = \frac{\omega\varepsilon''}{2}\int_V |\mathbf{E}|^2\, dV. \tag{3.2}$$

Hence, the absorption loss of the dielectric material is dependent on the electric field strength (E) in the tissue.

The quality factor (Q) of a small antenna can be used to approximate the radiation efficiency of the antenna with the user. The Q can be calculated from the frequency derivative of the unmatched input impedance of the antenna by using the expression[2] introduced in [125]. The calculated quality factor (Q_Z) takes into account the effect of the antenna element and the finite ground plane (effective Q, $Q_{0,eff}$). When the hand is included, its effect is also contained in Q_Z

$$\frac{1}{Q_Z} = \frac{1}{Q_{0,eff}} + \frac{1}{Q_{\text{hand losses}}}. \tag{3.3}$$

$Q_{0,eff}$ can be further divided into the quality factor of the antenna element ($Q_{0,\text{CCE}}$) and quality factor of the chassis ($Q_{0,\text{chassis}}$). The following relation exists between the η_{rad} and the Q of the antenna

$$\eta_{\text{rad}} = \frac{Q_Z}{Q_{0,eff}}. \tag{3.4}$$

In free space (no user-originated losses), we get the value for the $Q_{0,eff}$ as η_{rad} = 1. If we approximate that $Q_{0,eff}$ = $Q_{1,eff}$ in free space and with the hand, respectively, it is possible to calculate the η_{rad} directly from the antenna input impedance. For instance in [IV], it was possible to estimate the absorption losses of the hand at 900 MHz with a good accuracy using the Q_Z. By contrast, at 2000 MHz the Q-based η_{rad} (3.4) underestimates the effect of the hand. The explanation for this might be that a part of the hand is outside the reactive near field of the main resonator, meaning that the hand is causing also shadowing, and hence the prediction cannot be reliably made from the input impedance. Another reason for the wrong prediction at higher frequencies is discussed in [IV]: The main problem seems to be that at higher frequencies, the current distribution of the antenna structure diverges too much between the cases in free space and

[2]The equation is valid for electrically small antennas ($k_0 a < 1$, where k_0 is the wave number in free space and a is the radius of a sphere enclosing the antenna). If the equation is used for larger antennas ($k_0 a > 1$), the proper function of the equation needs to be verified (e.g., the antenna has to exhibit a single impedance resonance within its defined operating bandwidth).

with the hand, and thus the effective quality factor ($Q_{0,eff} \neq Q_{1,eff}$) is approximated in a wrong way that leads to an incorrect η_{rad}.

In spite of the fairly well-known effect of the user, commercial handset antennas are still often designed to have an optimal performance in free space and the performance characteristics with the user are just measured afterwards. An example of this can be found in [126] where the internal antenna element of the *Nokia N8* phone was designed, implemented and measured. The antenna performs very well in free space, but is sensitive to changes in its environment, suffering significantly from proximity to the user (particularly the hand). Nevertheless, the manufacturers of mobile devices are paying increasing attention to the user effect since the network operators will have increasing requirements for maximizing the radiation efficiency of handset antennas with the user and because a poorly working device will give bad publicity. This was demonstrated in 2010 by the case of the *Apple iPhone 4*, in which matching losses of its antenna increased up to 6.4 dB at GSM850 band when the user holds the device in such a way that the metal antenna is partly shorted out [127]. A more recent example of poor performance with a user is reported in [128]. A comprehensive study of popular handsets used in 2013 was conducted with a phantom hand and head in the talking mode. The measurements were made based on the CTIA and 3GPP standards [129]. The best performing handset (*Doro Phone Easy 605*) has an increase in losses of only 4 dB at the GSM900 band with the hand-head case compared to the free space case. As a comparison, the worst performing handset (*Nokia Lumia 925*) experiences 17 dB of additional loss in the same case. Both handsets have excellent performance in free space. Such performance degradation is difficult to explain only with the absorption losses of the hand and head tissues. Probably the frequency detuning causes considerable losses as well. At higher frequencies, the performance deterioration was significantly smaller. It is worth noting that the presented results are valid for the used hand and head phantoms, and the performance of the handsets can be different in real usage conditions.

A promising way to decrease the matching losses is to use frequency tuning [II], [20, 69–71, 130] or adaptive antenna tuner [131–134]. However, these kinds of methods tend to increase the complexity and power loss of the antenna implementation. An alternative approach is to design the matching circuit and antenna geometry in such a way that the

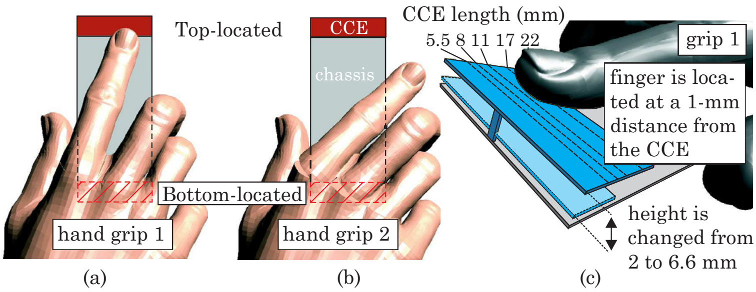


Figure 3.2. Used hand grips. (a) grip1 and (b) grip2. (c) Length and height of the CCE are changed from 5.5 to 22 mm and from 2 to 6.6 mm, respectively. The antenna element is located either in the top or bottom part of the structure.

impedance matching is not deteriorated substantially even if the user's hand is located next to the antenna element [I], [27, 28].

3.2 Effect of antenna dimensioning and location

The effect of different hand grips, hand positions and antenna types on the antenna performance has been investigated in many previous publications, for instance, in [VII], [107, 117, 135–138]. However, there are no published results on the way small changes in the dimensions and locations of handset antennas affect the interaction between the antenna and the user's hand. Such results would provide useful knowledge for antenna designers and could be utilized for designing antennas with reduced effect of the user.

In [IV], knowledge is increased by analyzing an extensive set of simulation series to demonstrate how the quality factor (Q), resonant frequency detuning (Δf_{r}) and decrease in radiation efficiency (η_{rad}) can be traded off with only minor changes in the antenna dimensions or location. As discussed earlier, the CCE antennas are especially suitable for this kind of parametric study and thus they are investigated with different dimensions and locations at 900 and 2000 MHz. The characteristics have been studied with a realistic CAD model of a phantom hand with two different grips. Grip 1, shown in Figure 3.2 (a), is based on standardization work [139] and grip 2 is similar to grip 1 except for the index finger being located on the chassis edge, see Figure 3.2 (b).

In Figure 3.2 (c), the studied lengths and heights of the CCE are shown. The tip of the index finger is always located at 1-mm distance from the CCE. The main trend seems to be that when decreasing the Q_{Z} by in-

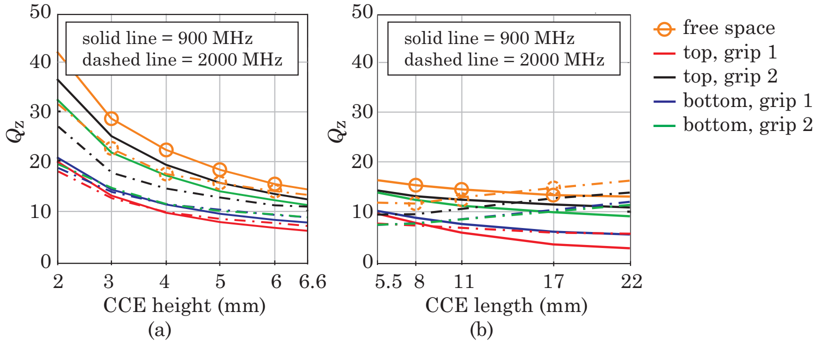


Figure 3.3. Quality factor as a function of CCE height and CCE length at 900 MHz and 2000 MHz.

creasing the CCE height or the CCE area (see Figure 3.3), there is only a minor effect on the η_{rad} (results presented in [IV]). However, the larger the CCE height or the CCE area is, the larger is the Δf_{r} resulting in decreased η_{tot} but also in wider impedance bandwidth. For example, when decreasing the height and area of the CCE it is possible to reduce the Δf_{r} and maintain the η_{rad} at the cost of impedance bandwidth. Instead, when the Q_{Z} is altered by changing the CCE location (results presented in [IV]) along the chassis, a distinct interconnection between the Q_{Z}, η_{rad} and Δf_{r} can be seen: a maximum in η_{rad} and a minimum in Δf_{r} occur when the Q_{Z} has its maximum.

Typically, the improvement of one property seems to deteriorate another. Hence, it is very challenging to design a handset antenna to have an optimal performance in all possible cases and frequency bands by using traditional antenna elements (e.g., PIFA or CCE). Based on the results shown in [IV], [27, 28], a part of the hand losses can be avoided by taking the effect of the hand into consideration in the antenna design. However, one can always have a grip that will ruin the performance of the antenna. One solution might be to invent new methods to excite the chassis wavemodes in such a way that the impact of the user can be minimized regardless of the hand grip, for instance without a traditional antenna element. Thus, a lot of research to build an environment insensitive handset antenna is still needed.

In addition to what is mentioned above, the location of the antenna element and the orientation of the antenna structure with respect to the propagation environment also have a significant effect on the polarization properties of the handset antennas [140]. One example is an integrated GPS antenna. For GPS, the intended polarization is right-hand circular polarization (RHCP), and it is obtained if the antenna element is located on the top-right corner of the device [140, 141], and the antenna structure is horizontally oriented. Because of this fact, the GPS antenna is typically located on the top-right corner in commercial handsets (see Figure 2.2).

3.3 Comparison between compact and large-sized antennas

In free space, the performance of the handset antennas typically becomes better when the antenna volume increases [21, 142, 143]. When the user's hand is present, the choice between a compact or large-sized antenna is not obvious. Despite this, there exists mostly studies concerning, for example, antenna selection [85, 104, 144], and knowledge on how the antenna size affects the total performance with the user is still, at least partly, missing.

In the previous section it was observed that by increasing the length or height of the antenna element, the hand losses remain almost constant in most cases [IV]. This suggests that the antenna element introduced earlier in Chapter 2 [I] can be made more compact without increasing the hand losses. However, this will increase the Q, thus narrowing the bandwidth and increasing the radiation losses (e.g., metal losses). As discussed earlier, the operational bandwidth can be kept sufficient by using a matching circuit with adaptive tuning component(s). Based on these facts, a compact frequency tunable antenna was introduced in [II]. This antenna structure consists of two antennas with MIMO capability, as shown in Figure 3.4 (b). Each antenna has 60% smaller area compared to the antenna introduced in [I] [see Figure 3.4 (a)].

Figures 3.4 (c) and 3.4 (d) compare the hand and mismatch losses of compact and large sized antennas. The positioning of the antenna structures is identical, but due to the different width of the antenna structures, the fingers (little finger, ring, middle) have slightly different locations. Despite this, some general trends can be found. At lower frequencies (below 1 GHz), the hand loss is less dependent on the element type and size because the chassis is the main radiator. At higher frequencies (above 1 GHz), the antenna elements become significant radiators, and therefore a larger portion of the losses are concentrated in the parts of the hand close to each element. As a conclusion, the large-sized antenna (hydrid antenna) has the largest hand losses at each frequency point studied. However, the difference to the second-worst element is not that significant

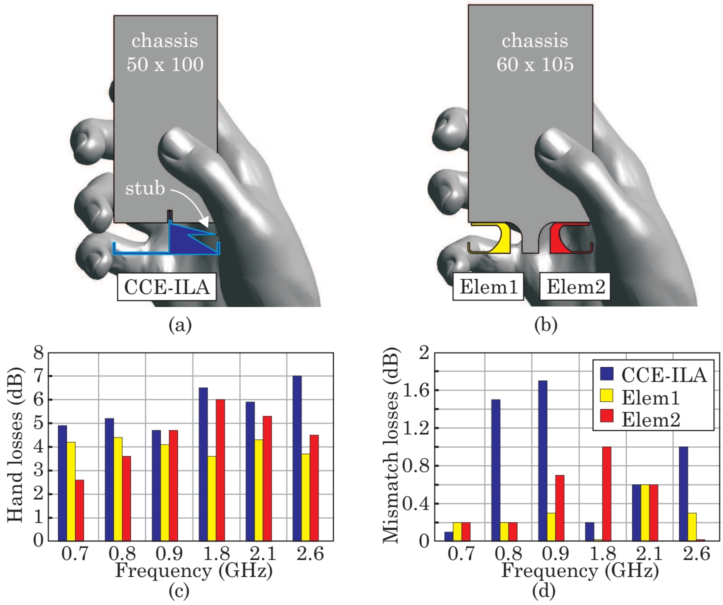


Figure 3.4. (a) Hybrid antenna with data grip. (b) Frequency reconfigurable antenna with data grip. (c) Measured hand losses. (d) Measured mismatch losses. The antennas are placed inside a polycarbonate enclosure.

in most cases, and can partly be explained by differences in hand grips. These results are thus consistent with the results presented in [IV]. When comparing the mismatch losses shown in Figure 3.4 (d), it can be seen that the large-sized antenna (hybrid antenna) can have quite significant mismatch losses (even more than 1.6 dB) in some cases, whereas frequency tuning is used in the small-sized antenna to compensate the impedance detuning. An extreme case of mismatch loss with the large-sized antenna occurs at 3.5 GHz. This resonance is created with a stub shown in Figure 3.4 (a). The open end of the stub is located in close proximity to the palm, which causes significant detuning and absorption losses (results presented in [I]). The total efficiency can be increased significantly in that particular case by flipping the handset by 180 degrees so that the open end of the stub moves close to the fingertips or by designing the stub in such a way that the open end of the stub remains further away from the hand in typical use cases.

Next, let us consider the limitations of antenna volume. One might conclude that the smaller the antenna, the better is the efficiency with the user. However, this is not true since the antenna Q will increase as the volume of the antenna decreases. Along with this increase in Q, the radiation efficiency of the antenna can drop significantly due to, for example metal, matching component, or substrate losses as discussed earlier.

As a conclusion, if the antenna volume is fixed, it is better to use multiple compact antennas and select the one operating best in each mode. The required frequency tuning can be implemented by using MEMS-based tunable capacitors, as discussed earlier in Chapter 2, and thus the tuning losses are reasonable [II], [69, 145]. This means that the overall efficiency of multiple compact tunable antenna can be better than that of a large-sized antenna.

3.4 User effect on multi-antenna system

Multiple-Input Multiple-Output (MIMO) can be used either to improve the link quality measured by diversity gain, or to enhance the data rate, measured by spatial multiplexing gain. Diversity is typically used in conditions where the channel fading is a problem (low-SNR), whereas spatial multiplexing is used in the high-SNR regime, where the system has limited degrees-of-freedom [146, 147].

In order to have a good multi-antenna performance, the system should have a sufficient isolation between the antennas and the mean effective gain (MEG) imbalance should be small [118]. In addition, the total efficiency (η_{tot}) of the antennas should be as good as possible and the envelope correlation coefficient (ρ_e) should be small enough to ensure the independence of the fading signals [148]. All these parameters are affected by the user. It is therefore important to study the effect of the user on MIMO performance as well. Extensive studies have been conducted concerning the isolation or the mutual coupling behavior of multi-antenna systems in the presence of the user [116, 118, 149–152]. In this thesis, the focus is on using the presented design rules to achieve a good multi-antenna performance in each usage condition.

The η_{tot} and ρ_e have a remarkable effect on the spatial multiplexing efficiency ($\tilde{\eta}_{mux}$) and effective diversity gain (EDG), as can be seen in the following formulas [153–156]

$$\tilde{\eta}_{mux} = \sqrt{\eta_1 \eta_2 (1 - \rho_e)}, \tag{3.5}$$

$$\text{EDG} \approx 10.48\sqrt{1 - \rho_e} \cdot \eta_{\text{best branch}}, \tag{3.6}$$

where η_1 and η_2 are the total efficiencies of antenna elements 1 and 2, respectively. The $\eta_{\text{best branch}}$ is the η_{tot} of the best antenna branch. The $\tilde{\eta}_{mux}$ defines the loss of signal-to-noise ratio (SNR) with respect to ideal MIMO

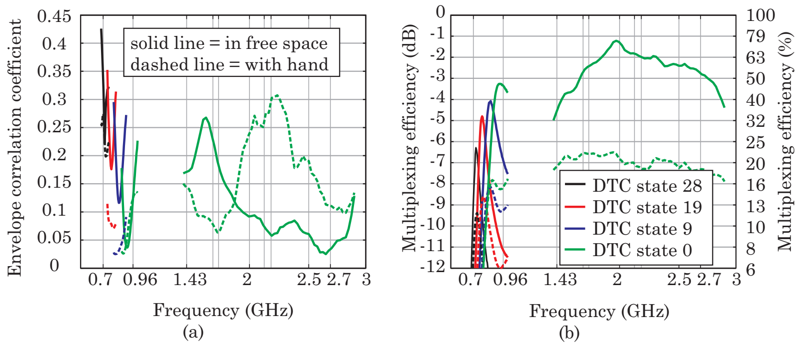


Figure 3.5. Measured (a) envelope correlations and (b) multiplexing efficiencies of proto 2 in free space and with the user's hand.

antennas whereas the EDG defines the improvement in SNR obtained from a multi-antenna system relative to a single-antenna system [157]. The above formulas are valid in isotropic environments. This kind of channel represents a rich reflection environment, such as indoors [96]. More complex propagation channels can be taken into account by using the MEG that combines the radiation performance of the antenna with the propagation characteristics of the surrounding environment. Such formulas are presented for example in [154].

A frequency reconfigurable MIMO antenna was introduced earlier in Chapter 2 [II]. In order to ensure the MIMO performance in different operating conditions, the antenna structure was measured with and without the user's hand. The measured ρ_e and the $\tilde{\eta}_{mux}$ results are presented in Figure 3.5. The ρ_e results suggest that the user's hand will improve the already good performance at the low-band. This is due to the shadowing effect of the hand [158]. At the high-band, the user's hand will improve the ρ_e between 1.43–1.8 GHz whereas the performance is better without the user at frequencies above 1.8 GHz. It can be seen that the user's hand will decrease the $\tilde{\eta}_{mux}$ performance by 3–5 dB at the low-band and by 2–5 dB at the high-band.

The MIMO capacity can be estimated from the ergodic capacity presented in Figure 3.6 [97]. The ergodic capacity is calculated by using a Rayleigh fast fading channel. The $\tilde{\eta}_{mux}$ results shown in Figure 3.5 (b) suggest that the channel capacity in free space is decreased by 18–40% and by 7–27% at the low- and high-bands, respectively, compared to the ideal 2x2 MIMO system (SNR $=$ 20 dB). In addition, the ergodic capacity of the proposed antenna outperforms the ideal SISO (Shannon theorem) system even in the worst case when the user's hand is present. Hence,

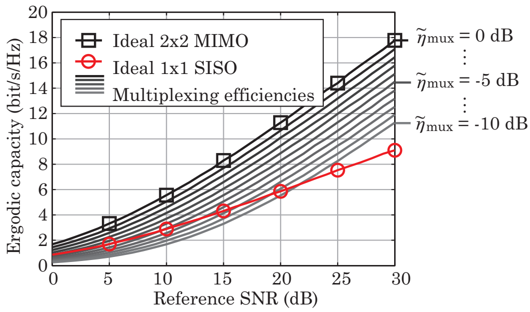


Figure 3.6. Ergodic capacities of different $\tilde{\eta}_{mux}$ values in a 2x2 MIMO system.

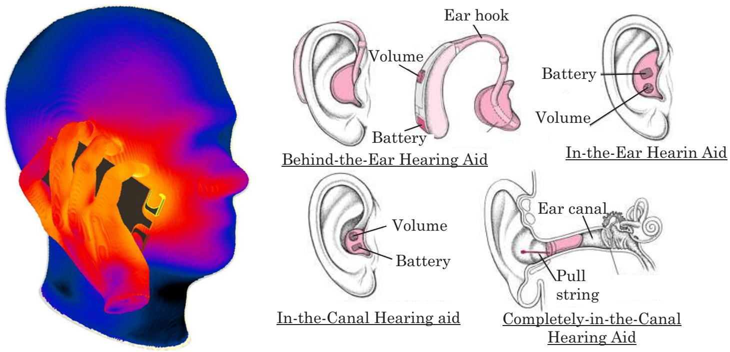
it is beneficial to use multi-antenna structures, even though the losses of multi-antenna structures are higher than those of single-antenna structure having the same volume.

In addition to the $\tilde{\eta}_{mux}$ performance, it is important to achieve a good EDG performance as well. The user's hand causes imbalance between the antenna branches, which can deteriorate the EDG performance and thus the power imbalance between the antenna branches should be smaller than 3 dB [96, 118, 159]. In an isotropic environment, the estimation can be made simple by comparing the hand losses of different antenna branches. Figure 3.4 suggests that the power imbalance of the frequency reconfigurable antenna presented in [II] is smaller than 3 dB, and thus a sufficient EDG performance can be achieved also with the used hand grip. However, the power imbalance will probably increase if a tighter hand grip is used. One solution is to increase the number of antennas, which increases the possibility that the user's hand is not fully covering the antenna element [85, 104, 151, 160, 161].

The above discussion and results presented in Section 3.3 suggest that the practical MIMO performance can be improved by using frequency reconfigurable antennas to reduce the effect of the user and thus improve the $\tilde{\eta}_{mux}$. However, a successful implementation of the frequency reconfigurable matching circuit requires the use of the MEMS-based DTC or switch components and a proper antenna geometry, as discussed earlier in Chapter 2.

3.5 Exposure limits and electromagnetic compatibility

The beginning of this chapter has discussed how the user can deteriorate the performance of the antenna. Next, the roles are reversed; dis-



(a) (b)

Figure 3.7. (a) Absorption of the electromagnetic radiation into the body tissues. (b) Different types of hearing aids[3].

advantages of the electromagnetic radiation of the handsets to the user are discussed. The electromagnetic radiation transmitted by a handset is discussed from three different points of view: 1) radiation safety aspects, 2) network aspects, and 3) electromagnetic compatibility.

1) **Radiation safety aspects**: According to the current knowledge, the main influence of electromagnetic radiation to the human body at the UHF-band is the rise in tissue temperature [1]. For the handset satisfying the safety margins [1,162], the temperature rise on the surface of the brain is shown to be not more than 0.2–0.3°C [163]. As a comparison, the normal fluctuation of body temperature is around $\pm 1°$C, and in exhausting physical exercise even a temperature rise of 2°C is quite common. However, it has been reported that electromagnetic radiation can accelerate production of cells [164] or it might open a leakage of albumin through the blood-brain barrier (BBB) causing neurological disorders [165]. Thus, it is very important not to exceed the safety limits of the electromagnetic radiation: Rather, the exposure should be as small as possible. In order to estimate the influence of the electromagnetic radiation, a measurement standard has been developed: the Specific Absorption Rate (SAR) is a measure of the rate of radio energy absorption in body tissue. The SAR is defined as the power absorbed per mass of tissue and has units of watts per kilogram (W/kg) [1].

2) **Network aspects**: The interest of the network operators is to optimize the link budget between base station and handset. An optimal link means that the base station can serve as many users as needed

[3]Image source: http://healthlob.com/2011/05/hearing-aid-types/

with a sufficient quality of services (QoS) [166]. The user of the handset will reduce the total efficiency of the handset (as discussed in Sections 3.1 and 3.2) and thus will deteriorate the link quality. To maintain the sufficient QoS, the network will automatically increase the transmit power of the handset or the base station depending on whether the handset is transmitting or receiving. However, the increased transmit power of the handset will increase the electromagnetic exposure of the user and decrease the battery life of the handset compared to the case with a smaller transmit power. In addition, the deteriorated link quality will decrease the cell size of the network increasing the cost for the operators [167]. Hence, it is very important to take into account the user's hand as well when designing a handset antenna. For instance with the talking grip, the user's hand absorbs a significant portion of the radiated power. In this case, the transmit power level should be increased, if the link quality is to be kept unchanged. However, the electromagnetic exposure toward the user's hand and head will increase [168, 169]. To obtain the smallest overall SAR, the antenna should be designed to perform efficiently in different usage conditions with the hand and/or head, and it should also be insensitive to their proximity.

3) **Electromagnetic compatibility**: As discussed earlier, the mobile handset antenna has to be designed to comply with the safety limits [1, 162] and maximize the transfer of electromagnetic energy between the base station and the mobile device. In addition, a mobile device used beside the user's ear may interfere with a hearing-aid device (see Figure 3.7) and thus the handset antenna should also fulfill the hearing-aid compatibility[4] (HAC) requirements [170]. These are problems that an antenna designer has to address. In the next chapter, some new ideas on how to reduce the electromagnetic exposure without significantly sacrificing the link quality are presented.

[4] In the USA, at least 50% of all marketed mobile handsets have to meet the HAC requirements. HAC is not requlated in EU.

4. New methods to reduce the interaction between the user and a mobile handset

In this chapter, different methods to reduce the electromagnetic exposure of the user and the interaction between the user and a mobile handset antenna are discussed. Section 4.1 considers the applicability of antenna phasing to decrease the head losses. A new method to decrease the effect of the hand and head on the operation of handset antennas is introduced in Section 4.2 [V,VI]. In Section 4.3, the benefits and drawbacks of balanced antenna structures in handsets are discussed [VII], and Section 4.4 investigates effective methods to control the near-fields [VIII]. Finally in Section 4.5, a short summary of the presented design guidelines are given.

4.1 Effect of phasing between antenna elements

Phasing between antenna elements can be used to decrease the user's effect on mobile handsets. One phasing scheme is shown in Figure 4.1, in which a phase difference is implemented for the antenna structure introduced earlier in [II]. Several different adaptive phasing schemes for handset antennas have been widely studied. In [158], the diversity performance of an adaptive handset antenna array was studied. It was concluded that if the weight factor (amplitude and phase) of each antenna element is optimally chosen, it is possible to increase the SNR and thus improve the diversity performance, even in close proximity to the user. Moreover, the adaptive reshaping of the radiation pattern by using antenna phasing has been studied in [171–173]. These studies were made at the frequencies of 2, 3.7, and 5.8 GHz. At higher frequencies, radiation pattern can be altered more through element phasing, as compared to that at lower frequencies. In the studied cases, adaptive antenna phasing was shown to improve the ρ_e performance significantly. An interesting passive phasing method to improve the impedance bandwidth and to

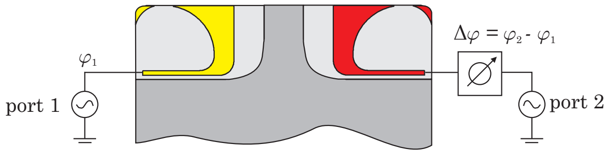


Figure 4.1. Phasing between the antenna elements.

decrease the user effect compared to a single-antenna system is introduced in [174, 175]. However, the findings are not that evident due to the changed antenna volume between the cases. In addition, the implementation of MIMO would increase the already large number of antennas. The reduction of SAR and head absorption by using antenna phasing has been studied, for example in [176–178], and the improvement of SAR is reported to be even 14 dB.

The above discussion suggests that antenna phasing is a very promising way to improve the diversity performance of the handset and to decrease its user effect. Next, the SAR performance of the frequency reconfigurable MIMO antenna introduced in [II] is examined. In addition, its usefulness and restrictions for a future handset are discussed. In MIMO systems, an additional challenge compared to the SISO case is to inspect the effect of multiple antennas on SAR. In order to estimate the need for additional SAR measurements, a metric called SAR to Peak Location Separation Ratio (SPLSR) is introduced in [179]. The SPLSR is defined as: $\mathrm{SPLSR} = (\mathrm{SAR}_1 + \mathrm{SAR}_2)/D$, where SAR_1 and SAR_2 are the SAR values (W/kg) of antennas 1 and 2, respectively. The separation between the SAR hotspots is denoted by D (cm). If D is less than 5 cm, the SPLSR has to be below 0.3 in order to avoid additional SAR measurements when both antennas are operating simultaneously.

The peak spatial SARs were simulated according to the stricter IEEE guidelines applied in the USA [1]. With the studied MIMO antennas (see Figure 4.1), the SPLSR requirement of 0.3 is not fulfilled, and thus additional measurements are required. It is shown that the SAR is significantly affected by changing the phase (φ) between the feeds [180]. Hence, the SAR is studied with simulations using three different phasings between the feeds. In the SISO mode, only one antenna is operating and the output power is set to 23 dBm (0.2 W), whereas in the MIMO mode, the total output power of 23 dBm is equally divided between both antennas (20 dBm each). In addition, a perfect impedance matching was computationally applied in order to have the worst case scenario.

Table 4.1. Simulated peak SAR values averaged over a 1-g mass of tissue.

	SISO		MIMO Phase difference			
Freq (MHz)	Elem1 (W/kg)	Elem2 (W/kg)	$0°$ (W/kg)	$90°$ (W/kg)	$180°$ (W/kg)	D (cm)
700	1.0	1.2	2.0	1.1	0.2	2.2
800	1.1	1.2	2.4	1.4	0.2	0.5
900	1.2	1.3	2.4	1.3	0.2	0.3
1800	1.0	1.4	1.3	1.1	0.9	2.5
2100	1.1	1.4	1.3	1.4	1.0	1.6
2450	1.0	1.3	1.4	1.4	0.9	2.3
2600	0.7	1.0	1.2	1.2	0.6	4.4

The effect of changing the phase on the SAR performance can be clearly seen in Table 4.1. The highest SAR is achieved when the E-field patterns generated by the two antennas are very similar ($\varphi = 0°$). On the other hand, the E-field pattern can be almost canceled if the fields are out of phase ($\varphi = 180°$) with respect to each other. This effect is not as pronounced at the high-band because of the increased distance between the hotspots, which results in a decreased coherence effect. It is good to note that the SAR can be intentionally manipulated, by changing the φ, only when the diversity mode is used, in other words, the same signal is radiated by both antennas. However, this is not trivial in an actual use case due to the changing state of the environment (e.g., user's hand may change the optimal phasing). When the multiplexing mode is used, phasing between the signals is random. Thus, the SAR can be high or low depending on the instantaneous phasing between the signals, making it impossible to intentionally manipulate the SAR. Nonetheless, the arithmetic average of the SAR over the simulated phase differences is between 1.0 and 1.3 W/kg, and thus the antenna fulfills the SAR requirements (i.e., SAR<1.6 W/kg).

4.2 Antenna shielding

Traditionally, the antenna element is placed on the backside of the mobile handset [4, 19], away from the head in the talk position, as shown in Figure 4.2 (a) (CCE1). This makes it easier to fulfill the radiation exposure restrictions (SAR limits) and improves the antenna performance in that use position. From the antenna operation point of view, this kind of antenna configuration is far from optimal for many other use positions. For instance, when using the handset in the data mode (browsing position), the user's palm or fingers may cover the antenna element [see Figure 4.2 (b)], reducing the radiation efficiency and causing frequency detuning, as

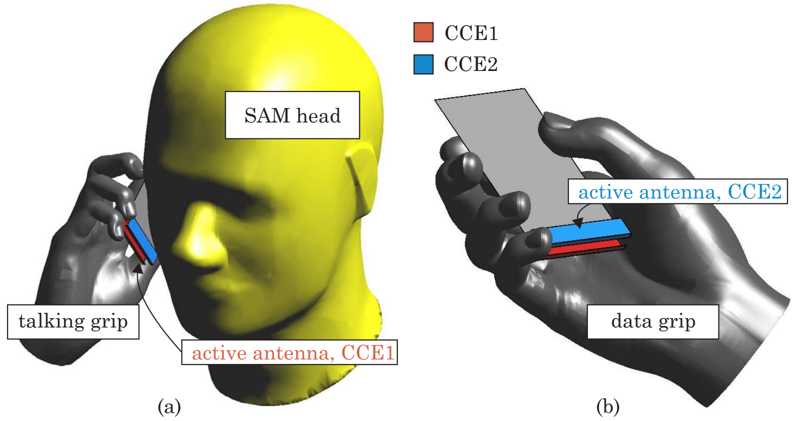


Figure 4.2. Example placement of the handset antenna (a) in talking position and (b) in browsing position.

discussed in Chapter 3. To solve the above-mentioned problems, an effective antenna shielding method for decreasing the effect of the hand and head on the operation of handset antennas is discussed in this section. The antenna shielding concept is introduced in [V] and the operation is verified by measurements in [VI].

The proposed shielded antenna structure shown in Figure 4.3 consists of two non-self-resonant type CCE antennas on top of each other. Here, an active antenna element refers to the case where the antenna element is switched on (feed connected) and a passive element refers to the case where the antenna element is switched off (floating or connected to the ground, see Figures 4.3 (a) and 4.3 (b). The operating principle of the shielded structure is such that one antenna element is active at a time and the other is passive. If the passive element is not connected to the ground, the antenna structure can be treated as an off-ground structure[1]. If the passive element is connected to the ground, as shown in Figure 4.3 (b), it can be considered as an extension of the ground plane to improve the shielding effect towards electromagnetic exposure. The simplest and a cost efficient way to implement the selection of the antenna element is to utilize the information of the current operating mode (talking/browsing). If the talking mode is used (handset beside the head), the antenna element placed on the back side of the handset is selected [see Figure 4.3 (c)], and the passive antenna element is operating as a shield on the side of the head of the handset. When the head is not beside the handset, the

[1]Since the passive element has a self-resonance at 1660 MHz, the effect of the floating element can be ignored at 900 MHz. At 2000 MHz, the effect of the floating element is still almost non-existent.

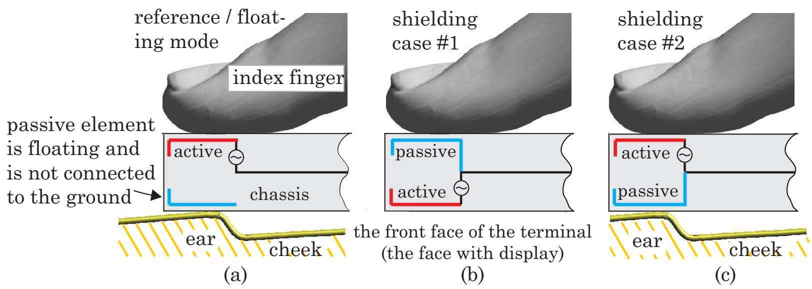


Figure 4.3. Antenna structure having active and passive antenna elements. (a) reference structure or the case having a floating passive antenna element, (b) shielding Case #1, and (c) shielding Case #2. Dimensions are in millimeters.

Table 4.2. Improvement of η_{tot} and change of SAR values in the hand and head compared to the reference antenna. Green and bold values refer to cases with improvement compared to the reference.

Freq. (MHz)	Structure Case #	$\Delta\eta_{\mathrm{tot}}$ (dB) hand	head	hand+head	Δ SAR (%) hand	head	head+hand
900	#1 top	**2.9**	-2.8	**2.6**	**-45**	+8	+40
900	#2 top	**0.1**	**1.8**	**5.0**	+19	**-50**	**-81**
900	#1 bottom	**0.9**	-2.2	-1.4	**-16**	+24	+29
900	#2 bottom	**0.2**	**0.6**	**0.7**	**-0.4**	**-20**	**-18**
2000	#1 top	**0.9**	-1.1	**1.2**	**-53**	+14	+31
2000	#2 top	**0.4**	**0.6**	**2.1**	**-32**	**-49**	**-43**
2000	#1 bottom	**0.7**	-1.5	-1.5	**-37**	+74	+94
2000	#2 bottom	0.0	**0.7**	**1.3**	**-12**	**-26**	**-38**

At 900 MHz SAR values are normalized to 0.25 W input power (+24 dBm power class).
At 1800 MHz SAR values are normalized to 0.125 W input power (+21 dBm power class).
SAR is calculated over 10 g of body tissue.
SAR of underlined tissues are considered.

antenna element placed on the front face of the handset is active, as can be seen in Figure 4.3 (b).

In order to verify the promising numerical results introduced in [V], two prototype antennas were built and measured. The operation is demonstrated at the 860–960 MHz and 1590–2500 MHz frequency bands. More detailed results are presented in [VI].

The simulated results shown in Table 4.2 indicate that the shielded antenna structure has two specific operating modes at 900 MHz: In Case #1 top, the η_{tot} with the hand can be improved by 2.9 dB compared to the reference structure, and in Case #2 top the η_{tot} with the hand and head can be improved by 5 dB compared to the reference. The benefit of the shielded antenna structure is clearly larger when the antenna elements are top-located. The shielded top-located antenna structures outperform the widely used bottom-located antennas by a large margin.

At 2000 MHz, the improvements are not as significant as at 900 MHz. The improvement in the η_{rad} with the hand is 1 dB and with the hand

and head 2.2 dB. This is mainly due to the fact that the passive antenna element has a self-resonance at 1660 MHz and thus the passive element is no longer as good an extension of the ground plane as at 900 MHz. The shielding effect is improved at higher frequencies by connecting the passive element to the chassis with multiple connections. However, this approach will lead to an increased complexity and the benefit will be partly or fully lost. Another method to avoid the deteriorated performance at higher frequencies is to shift the self-resonance of the CCE to higher or lower frequencies. This can be done, for instance, by changing the dimensions of the CCE.

A significant improvement in the hand and head SARs can be seen with the shielded antenna structure compared to the reference structure. For instance, the shielding structure can decrease the SAR in the hand by 45% at 900 MHz, when the index finger is covering the antenna element. Moreover, the head SAR can be decreased by 81% at 900 MHz with hand and head, when the antenna is top-located. At 2000 MHz, the improvement in SAR values is smaller but still about 30–50% improvements in the hand and head SARs can be achieved. It is good to note that the improvement of the SAR also improves the total efficiency (η_{tot}), as could be expected.

With the hand, the main part of the improved η_{tot} and η_{m} is caused by the increased distance between the index finger and the active antenna element. The passive antenna element acting as a shield helps to decrease the hand absorption only by 0.2 dB [V], whereas the improvement in SAR is mainly due to the shielding effect of the passive antenna element.

The reference structure used in this study is off-ground-type which naturally has larger SARs compared to on-ground-type antennas, as discussed earlier in Section 2. In [V], the used reference was on-ground-type and the improvements in the η_{rad} with hand, head, and hand+head were 3.6, 2.8, and 1.9 dB, respectively at 900 MHz. The improvement in head SAR was about 44%. Hence, the shielded antenna structure outperforms also the on-ground-type reference antenna. In the hand-only case it is useful to have the passive element floating [see Figure 4.3 (a)], providing better bandwidth around 900 MHz. However, it is not beneficial to use the floating element with the head since the shielding effect is lost and the SAR is increased.

Considering practical applications, the shielding structure requires a switching system which was not implemented in this study. If the implementation losses, approximately 0.3–1 dB with current technology [7, 181], were added to the results, the shielded structure would still perform much better compared to the reference. In addition, a semiconductor component such as a transistor switch would raise the problem of distortion of the switching system [10, 182–184]. One major disadvantage of shielding is increased antenna volume. The available volume for antennas in current handsets is very limited and thus it would be very challenging to combine efficient shielding and multi-antenna functionality within a small handset. One possibility would be to use frequency tuning in order to decrease the volume of an individual antenna element [II]. Another drawback of the shielded antenna structure is the increased complexity and the fact that the greatest benefit is achieved when the antenna is top-located – nowadays, most of the main handset antennas are bottom-located, as shown previously in Figure 2.2.

4.3 Balanced antenna structures

The idea of using balanced antenna structures in mobile handsets originates from the fact that a balanced antenna can be electrically isolated from the handset chassis, unlike a typical unbalanced handset antenna such as PIFA or CCE. Especially at the lower UHF-frequencies (below 1 GHz), a significant portion of the radiated power of a traditional handset antenna originates from the chassis, as shown in Figure 4.5 (a). In these structures, the effect of the user can be significant: the matching changes and the radiation efficiency decreases regardless of whether the antenna element itself is covered by the lossy tissue or not, as discussed in Chapter 2. Hence, the use of a balanced antenna structure might be reasonable keeping in mind that the chassis is then not used on purpose as a radiator, thereby isolating the antenna from the chassis, as shown in Figure 4.5 (b). The level of isolation describes the ability of the balanced antenna to reject the electromagnetic coupling to the wavemodes of the chassis. This depends strongly on the antenna structure used, frequency, and the relative location between the antenna and the chassis [VII], [185]. Typically, the closer the balanced antenna is to the chassis, the narrower is the impedance bandwidth (see Figure 4.4) [VII], [185]. This is mainly due to an increased mirror image effect caused by the chassis that rejects the radiation of the balanced antenna.

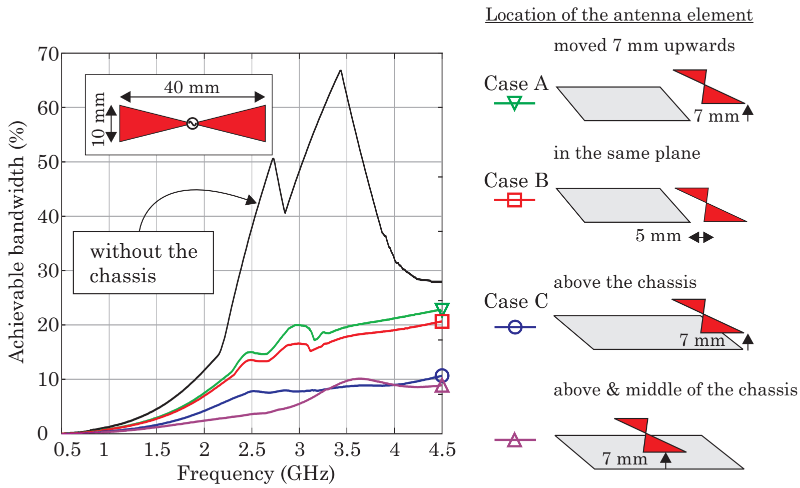


Figure 4.4. Achievable bandwidth potentials of a small bow-tie element in different antenna positions. The bandwidths are calculated by using the matching criterion of optimal overcoupling [64]. In all cases the total length of the structure is 100 mm.

4.3.1 Feasibility of balanced antennas

The aim of the study made in [VII] was to investigate the feasibility of balanced antennas in the handset environment. The features of interest are the following: *a*) EM isolation between the antenna element and the chassis, *b*) bandwidth potential of the balanced antenna close to the chassis, and *c*) interaction between the user and the antenna. The most promising balanced structure seems to be a small bow-tie antenna shown in Figure 4.5 (b) [VII], [185]. At frequencies below self-resonance, an additional matching circuit is needed. The benefits of using the balanced antenna below the self-resonance are that the coupling to the chassis is quite weak, and that the antenna element is small in size. Another approach to isolate the antenna from the chassis would be to use folded-dipole-type antennas discussed in [186–189]. Those antennas have typically different radiating modes depending on the frequency and thus the balanced mode is achieved only in a certain band (in those cases around 1.8–2 GHz). Here, the focus is on the characteristics of the small bow-tie.

As discussed earlier, the utilization of the chassis currents increases the effective antenna size and therefore balanced antennas have to be made larger than traditional antenna elements, such as the PIFA or CCE, in order to have the same impedance bandwidth. To keep the size of the antenna small enough to fit inside a handset, a narrower instantaneous impedance bandwidth has to be accepted for the balanced antenna com-

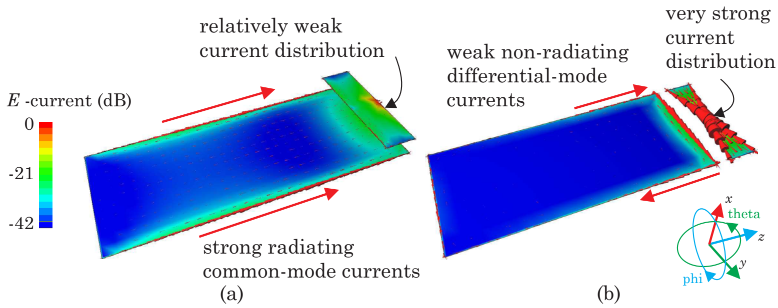


Figure 4.5. Simulated current distributions of the (a) CCE structure, and (b) bow-tie structure at 1800 MHz. The maximum E-current is 10 A/m.

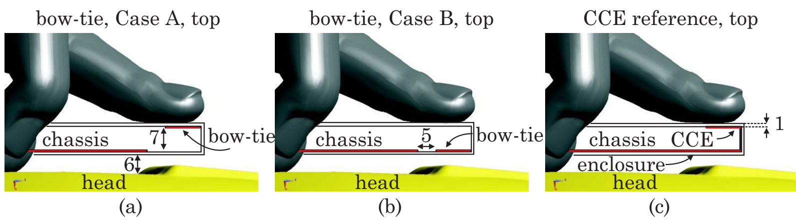


Figure 4.6. (a) Bow-tie is placed next to the index finger, (b) bow-tie is placed at the same plane as the chassis, and (c) CCE is placed next to the index finger. All dimensions are in millimeters.

pared to the traditional elements.

Observations on the main benefits and drawbacks of balanced antennas can be seen in Figure 4.5. The bow-tie is fairly well isolated from the chassis, which can be seen from the weak differential currents along the long edges of the chassis. Conversely, the bow-tie has much stronger electric fields close to the antenna element compared to the traditional CCE antenna (see Figures 4.7 and 4.8). This will cause problems when lossy tissue is located close to the antenna. In [VII], the performance of balanced antenna structures with the user was compared to a traditional antenna (denoted as CCE reference in Table 4.3). Two different positions for the bow-tie antenna element are used: in *Case A* the antenna element is moved 7 mm upwards from the chassis, and in *Case B* the antenna element and the chassis are located in the same plane (see Figures 4.4 and 4.6).

Several observations (a-e) can be made based on the results of Table 4.3:

a) The small bow-tie is quite robust to the distance between the index finger and the antenna element in terms of frequency shift. This is probably due to the used hand grip; the index finger is in a position where magnetic field is strong and electric field is weak. Dielectric loading due to finger does not consequently affect much the operation of the antenna.

b) The frequency shift of the balanced bow-tie antenna is much smaller than that of the reference antenna at 900 MHz. At 1800 MHz, the shift is almost the same, especially if the antenna element is bottom-located.

c) The balanced bow-tie performs best when the antenna element is top-located. When the antenna element is bottom-located, the palm decreases the resonant frequency and absorbs more power than in the top-located case.

d) When comparing the radiation efficiencies with hand or head it can be seen that the distance between the antenna element and the tissue (hand or head) has a huge impact on antenna performance; the closer the bow-tie is to the tissue, the lower is the radiation efficiency and the higher is the SAR. It is interesting to observe that the radiation efficiency of the reference antenna is practically the same in the bottom- and top-located cases at 900 MHz. This is mainly due to the fact that the chassis is the main radiator at lower frequencies, as discussed earlier.

e) The SAR is very high (clearly exceeding the safety limits) for the bow-tie structure when the antenna element is close to the head in *Case B*. One can also see that when moving the antenna structure 7 mm upwards in *Case A* it is possible to decrease the SAR by 30% at 900 MHz and by 60% at 1800 MHz. Hence, the SAR results agree with the results of the shielded antennas; it is very beneficial for antenna performance to increase the distance between the radiator and lossy tissue [12]. The SARs were studied in the bottom-located cases and are assumed to be a bit higher when the antenna elements are top-located [VI]. The SAR performance of the bow-tie can be improved by using an EM shield at the cost of decreased impedance bandwidth (see Figure 4.4).

Figure 4.4 presents the achievable bandwidth potentials[2] of a small bow-tie element in different antenna positions. It can be observed that below 1 GHz the bandwidth is very limited regardless of antenna position, and frequency tuning is required when implementing balanced antennas for real handsets [II], [6, 7, 10, 20, 69, 145, 190]. This study focuses on the feasibility of balanced antennas and thus it is assumed than an

[2]The concept of achievable bandwidth potential is discussed in detail in [30].

Table 4.3. Effect of the user's hand or head on matching, radiation efficiency, and SAR at 900 MHz and 1800 MHz. Green and bold values refer to cases with improvement compared to the reference.

	900 MHz				1800 MHz			
	with hand		with head		with hand		with head	
Structure	Δf_r (%)	η_{rad} (dB)	SAR (W/kg)	η_{rad} (dB)	Δf_r (%)	η_{rad} (dB)	SAR (W/kg)	η_{rad} (dB)
CCE reference, top	-5.8	-3.4	-	-	-3.6	-4.4	-	-
CCE reference, bottom	-4.1	-3.2	2.4	-5.2	-1.8	-2.8	1.2	-3.3
bow-tie, case A, top	**-1.8**	**-2.8**	-	-	**-1.6**	**-1.7**	-	-
bow-tie, case A, bottom	**-3.2**	-4.9	2.7	**-4.2**	-3.6	-3.2	**0.9**	**-2.1**
bow-tie, case B, top	**-1.7**	**-1.1**	-	-	**-1.7**	**-0.9**	-	-
bow-tie, case B, bottom	**-2.3**	-4.6	3.9	-8.5	-2.4	-2.8	2.2	-4.1

At 900 MHz SAR values are normalized to 0.25 W input power (+24 dBm power class).
At 1800 MHz SAR values are normalized to 0.125 W input power (+21 dBm power class).
SAR is calculated over 10 g of body tissue.

efficient frequency tuning method is available. Different frequency tuning techniques and implementation challenges of high-Q structures were discussed earlier in Chapter 2. At higher frequencies (above 2 GHz) the achievable bandwidth is acceptable, especially without the chassis. The worst case is obtained when the balanced antenna is located above the chassis, in which case the achievable bandwidth can be reduced even by 70%.

4.4 Near-field control of handset antennas

The inherent, strong reactive electromagnetic near-fields of the handset may cause problems for the operation of a hearing-aid device. Strong near-fields often result in a high SAR, in which case the transmit power may need to be reduced to comply with the SAR specifications. A typical handset antenna utilizes the chassis of the handset as a radiator, as discussed earlier, for example in Section 4.3. Therefore, the chassis has a substantial effect on the near fields of the handset. The current distribution of the chassis resembles that of a thick dipole [24], and thus the electric fields at the ends of the chassis are typically strong [see Figures 4.7 (a) and 4.7 (c)]. One method to control the near fields would be to somehow modify the chassis geometry. One can, for instance, change the dimensions or shape of the chassis. However, the display of the mobile device and other design factors set strict restrictions on how to the chas-

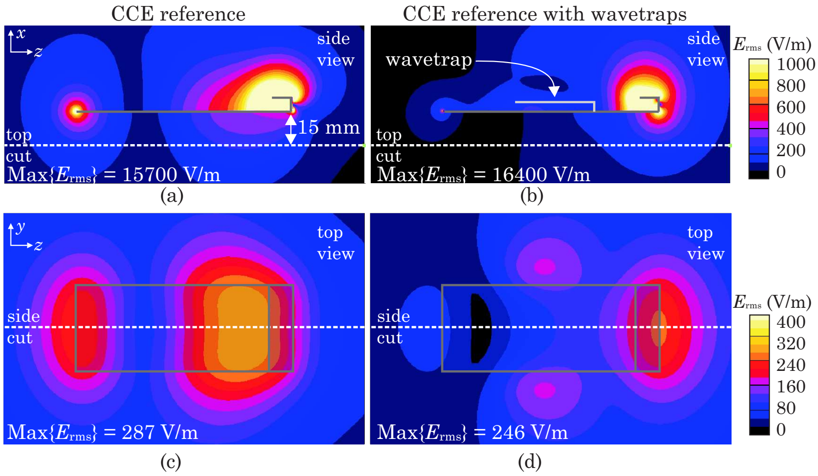


Figure 4.7. Electric field distributions of the CCE reference and the CCE reference with wavetraps at 1880 MHz. The side views of the structures are presented in (a)–(b), and the top views are presented in (c)–(d). The field values of the side view are taken from the center of the handset (see dashed line of side cut). The field values of the top view are taken at a distance of 15 mm from the chassis (see dashed line of top cut). In all cases, the input power is normalized to 1 W and impedance mismatch is excluded. The maximum root mean square of the electric field strength (Max$\{E_{\mathrm{rms}}\}$) is calculated on each plane.

sis can be modified. Actually, the display behaves as a part of the chassis [see Figure 2.2 (a)] and thus the chassis cannot be significantly shaped or patterned. In general, the larger the dimensions of the chassis are, the lower are the reactive near fields. Thus, handsets with larger dimensions will inherently have better SAR and HAC performance compared to handsets with smaller dimensions [12]. In addition, the sensitivity of the hearing-aid device to electromagnetic fields depends on the modulation technique used. The pulsed RF signals of Time-Division Multiple-Access (TDMA), such as GSM, are more harmful than those of Code-Division Multiple-Access (CDMA) where the signal power is spread uniformly over the bandwidth [170, 186]. In addition, the peak transmission power of, for example, LTE systems is noticeably lower than in GSM (24 dBm and 33 dBm, respectively). CDMA handsets have therefore inherently better HAC than GSM handsets.

An effective way of controlling the reactive near fields of the handset has first been introduced in [191]. The idea is based on the manipulation of the chassis wavemodes with a parasitic radiator or wavetrap. The wavetrap can cancel a part of the near field, thus decreasing the SAR and increasing the realized efficiency. The idea was also used in [192], where the wavetraps were shown to broaden the impedance bandwidth

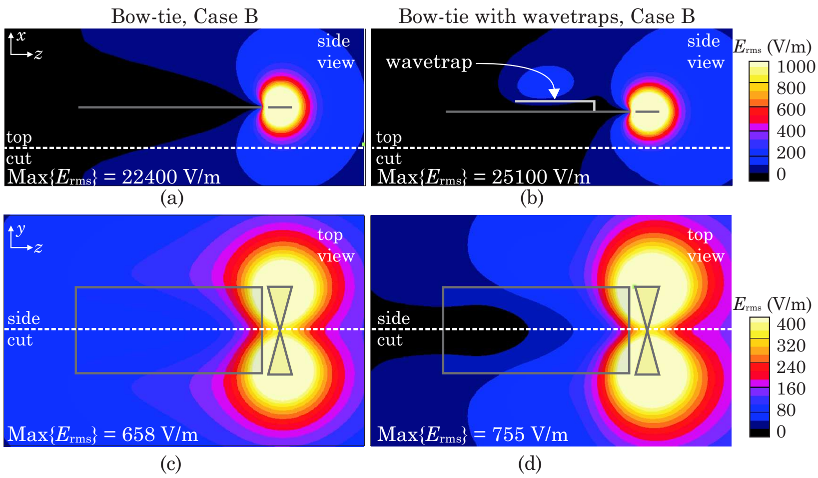


Figure 4.8. Electric field distributions of the bow-tie antenna without and with wavetraps at 1880 MHz. The side views of the structures are presented in (a)–(b), and the top views are presented in (c)–(d). The field values of the side view are taken from the center of the handset (see dashed line of side cut). The field values of the top view are taken at a distance of 15 mm from the chassis (see dashed line of top cut). In all cases, the input power is normalized to 1 W and impedance mismatch is excluded. The maximum root mean square of the electric field strength (Max$\{E_{\mathrm{rms}}\}$) is calculated on each plane.

at higher UHF-frequencies (around 2 GHz). The idea was developed further in [VIII], where the wavetraps create a high-impedance condition on a desired location on the chassis. Thus they modify the chassis wavemode by manipulating the current distributions of the chassis, and so the electric and magnetic fields in the end of the chassis opposite to the antenna element are decreased [see Figures 4.7 (b) and 4.7 (d)] by manipulating the current distributions of the chassis. As can be seen in Table 4.4, the wavetraps can decrease the electric and magnetic fields on the HAC plane [VIII], [170, 193] by up to 75% and 70%, respectively. It is also seen that the electric field is directed away from the head (from the lower part of the handset) which enables to decrease the SAR in the head by 23% at 1880 MHz compared to the case without wavetraps [VIII].

The disadvantages of the wavetraps are related to strict requirements on the length of the wavetrap; it should equal a quarter of the wavelength, and the resonance is typically rather narrow, as can be seen in Figure 4.9. Moreover, the tissue of the user close to the wavetrap changes the electric length of the wavetrap, as discussed in Section 3.1. Thus, the effect of the user has to be taken into account in the design process. Multiresonant or tunable wavetraps may increase the operational bandwidth and might improve the operation with the user [194, 195]. In addition,

Table 4.4. Summary of the simulated peak field values on the HAC plane.

Structure	Electric field (V/m)		Magnetic field (A/m)	
	836 MHz	1880 MHz	836 MHz	1880 MHz
reference	551	250	0.67	0.60
reference with wavetraps	-	63	-	0.18
bow-tie, case B	73	73	0.29	0.24
bow-tie with wavetraps, case B	-	26	-	0.09
HAC specification field (peak) limits M3 (AWB = -5 dB)	<266.1	<84.1	<0.80	<0.25
HAC specification field (peak) limits M4 (AWB = -5 dB)	<149.6	<47.3	<0.45	<0.14

At 836 MHz field values are normalized to 2 W (+33 dBm) input power.
At 1880 MHz field values are normalized to 1 W (+30 dBm) input power.

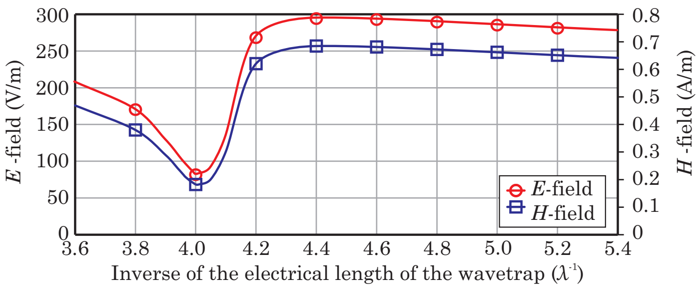


Figure 4.9. Effect of the length of the wavetrap on the E- and H-fields on the HAC plane at 1880 MHz. The best performance is achieved when the length is $\lambda/4$.

at the lower UHF frequencies, the wavetrap might be impractically long or the achieved operational bandwidth would be too narrow (even with additional impedance tuning) to be used in handsets. Thus the operation of wavetraps is in practice limited to higher UHF-frequencies above 1.8 GHz. In a real handset, the wavetraps will require special arrangements in phone mechanics, for instance, cable outputs might not be placeable under the wavetraps. In addition, the display located close to the wavetrap might deteriorate the performance of the wavetraps or there might be additional antennas located on the long side of the chassis, as is done, for example, in the *Nokia Lumia 920* phone. One possible implementation of wavetraps would be to ground, for example, the display or battery in such a way that it acts like a wavetrap and creates a high-impedance condition at a desired location on the chassis [191].

Another way of controlling the reactive near fields is to use isolated antenna structures. The chassis can be fully or partly isolated from the antenna element depending on the technique used [VII], [186]. Here, the focus is on balanced antennas, and the bow-tie antenna discussed in Section 4.3 is used as an example of an isolated antenna. As can be seen in Figures 4.7 and 4.8, the electric field at the open end of the chassis is decreased considerably compared to non-isolated antennas (CCE reference). Moreover, the electric field can be decreased even more at the open end of the chassis with the help of the wavetraps. This is done at the cost of increased field values near the antenna element compared to the CCE reference (see Max$\{E_{\mathrm{rms}}\}$ values in Figures 4.7 and 4.8). By contrast, this will increase the SAR values as discussed earlier. It is seen in Table 4.4 that the bow-tie antenna can fulfill the tight M3 specification of the HAC standard even without the wavetraps and it is possible to improve the HAC performance even further by using the wavetraps to fulfill the more strict M4 specification [170, 193]. Probably the SAR performance can also be slightly improved with the help of the wavetraps since they can direct the fields away from the head [see Figures 4.8 (b) and 4.8 (d)], as discussed earlier.

As a general conclusion, modifying the reactive near fields will change the field distributions of the antenna structure, as can be seen in Figures 4.7 and 4.8. This can cause increased field values at certain locations, especially if the radiated power is kept constant, thereby causing other problems such as increased SAR in the hand. In the case of wavetraps, the field is directed upwards from the chassis (away from the head), which makes it possible to improve both HAC and SAR performance at the same time. In the case of the balanced bow-tie, the chassis is not used as a radiator, meaning that the fields are concentrated near the antenna element. This will lead to an extremely good HAC performance but on the other hand the SAR becomes rather high.

4.5 How to design environment insensitive handset antennas?

To conclude the work presented in this thesis, a short summary of the proposed design guidelines is given. The guidelines can be used to design small-sized, multiband and efficient handset antennas that are environment insensitive. Guidelines have been developed primarily for non-resonant antennas, but with some limitations, they can be used for other types of antennas as well.

1) The distance between the user and the antenna element(s) should be

maximized. Typical use cases with different hand grips have to be studied. Special attention should be given to the open ends of the antenna geometry, where E-field maxima can occur. In addition, the antenna should be geometrically simple to make it more tolerant of user originated losses. By using multiple small-sized antennas, the probability of them all being in close proximity to the user can be decreased.

2) Frequency tuning can be used to decrease the antenna volume and to compensate for impedance detuning. In order to achieve a wide tuning range and reasonable tuning circuit losses, the antenna geometry has to be carefully designed. One way of achieving this is to use a nonresonant antenna element having a large radiation conductance across the whole band.

3) Multiple antennas can be used both to decrease the effect of the user and to increase the data rate. However, as the number of antennas increase, decreased isolation between the antenna elements need to be accepted. This is challenging for the isolation between the antennas. Broadband decoupling techniques are typically very complex and can decrease the radiation efficiency if located in the vicinity of radiating structures. One potential method is to use a combination of balanced and unbalanced antennas (BUB) to achieve a high isolation between the ports. In addition, the antenna geometry and placement should be chosen in such a way that the open ends are pointing away from each other.

4) A wideband and simple handset antenna can be designed by combining a nonself-resonant CCE, a self-resonant ILA and a simple high-pass type matching circuit. The CCE should be designed to have a strong coupling to the lowest-order chassis wavemode, as it is responsible for the low-band operation. Typically, this means that the element should maximally utilize the available antenna volume. The high-band operation is achieved by further modifying the antenna geometry to have a self-resonant operation.

5) The antenna should be optimally overcoupled to provide wideband impedance response. This ensures that the antenna operates efficiently also in vicinity of the user.

6) The operation of the chassis can be manipulated by using wavetraps. This enables, for example, decreasing the SAR, broadening the imped-

ance bandwidth, and weakening the interference between a hearing-aid device and the handset. The wavetraps may be formed, for example, by grounding a display or battery in an appropriate way.

7) The main antenna or antennas have to be placed at the bottom part of the device in order to fulfill the SAR and HAC requirements. The auxiliary antennas that are mainly used for reception, can be placed more freely. However, the optimal locations for auxiliary antennas are frequency-dependent and should therefore be chosen carefully.

5. Summary of publications

[I] Design Strategy for 4G Handset Antennas and a Multiband Hybrid Antenna

A novel design strategy for multi-standard mobile handset antennas is presented and verified with experimental results. It is shown that by using a geometrically simple CCE antenna and by modifying its feeding strip in a clever way, extremely wideband antenna covering all the LTE-A bands can be obtained. The results show that the presented antenna operates with better than 3 dB (50%) efficiency across the frequencies of 698-2900 MHz and 3250-3600 MHz, thus having state-of-the-art performance. It is demonstrated how the multi-antenna functionality can be included within the antenna structure, simultaneously achieving a small antenna volume.

[II] Multiband Frequency Reconfigurable 4G Handset Antenna with MIMO Capability

A novel, frequency reconfigurable 4G MIMO handset antenna is presented and verified with experimental results. Frequency tuning is used to minimize the antenna volume and to compensate for the losses caused by user-originated impedance detuning. Both antenna elements are independently frequency reconfigurable and can cover most of the LTE-A bands. The study compares the losses of CMOS- and MEMS-based digitally tunable capacitors (DTC). In addition, a new method is introduced to estimate the suitability of the antenna geometry for frequency tunable antennas.

[III] Isolation improvement method for mobile terminal antennas at lower UHF band

In this paper, a new method to improve the isolation between antenna elements on a mobile terminal at the 900-MHz frequency band is presented. The characteristics of dual-antenna systems have been studied by simulations. The purpose is to use a combination of balanced and unbalanced antenna structures. In addition, the diversity performance is investigated in three different radio propagation environments. It is shown that the proposed structures can achieve up to 100 dB port-to-port isolation and effective diversity gain of 10 dB in an urban propagation environment.

[IV] Mobile terminal antenna performance with the user's hand: effect of antenna dimensioning and location

A systematic simulation study on the performance of mobile terminal antennas is made in the vicinity of the user's hand. The effects of antenna dimensioning and antenna location on the ground plane of the device are demonstrated. The studied performance parameters are quality factor, radiation efficiency, and frequency detuning. Based on the results, beneficial approaches and general guidelines for antenna designs with a reduced effect of the user's hand are given.

[V] Antenna shielding method reducing the interaction between user and mobile terminal antenna

A new method to decrease the effect of the hand and head on the operation of mobile terminal antennas at the 900 MHz frequency band is introduced. The proposed structure consists of two antenna elements. Depending on the use position, the better-performing antenna element is selected and the other is acting as a shield.

[VI] Reducing the interaction between user and mobile terminal antenna based on antenna shielding

In this paper, the idea presented in [V] is verified by measurements. The obtained results show that the proposed structure can increase the total efficiency with the hand and head by 5.0 dB and decrease the head SAR values by 81% at 900 MHz compared to a traditional single element structure. At 2000 MHz, the benefits are 2.1 dB and 43%, respectively. The shielding structure can also be used to significantly decrease the SAR in the hand.

[VII] Balanced antenna structures of mobile terminals

The feasibility of balanced antenna structures in the mobile terminal environment has been investigated in terms of bandwidth and radiation properties. It has also been studied whether the effect of the user's hand on frequency detuning and decrease in radiation efficiency could be reduced using balanced antenna structures compared to traditional antenna structures. In addition, emphasis has been put on the SAR and HAC performance of balanced antenna structures.

[VIII] Near-field control of handset antennas based on inverted-top wavetraps: focus on hearing-aid compatibility

The paper introduces a new way of controlling the near-fields of a handset antenna by using quarter-wavelength resonators. The local reduction of the near-fields is especially important for the operation of the hearing-aid of the user. The reshaping of the near-fields may also enable reduced SAR values.

6. Conclusions

This doctoral thesis focuses on handset antennas. The work contributes to designing antennas for future handsets having a small size, multiband operation, good environment-insensitivity and well-performing frequency tuning.

The volume reserved for the handset antennas is very limited. At the same time the number of frequency bands is increasing and requirements for reliable high-speed Internet connections are growing. In order to solve these challenges, new antenna techniques and research are needed. In this work, it is shown that a part of the hand losses can be avoided by taking the effect of the hand into consideration during the antenna design [IV]. Partly based on these results a novel, compact hybrid antenna is proposed [I]. It combines the advantages of typical self- and non-self-resonant handset antennas. It is also demonstrated that a simple, almost optimally overcoupled antenna geometry can result in a very robust antenna in close proximity to the user. To further decrease the volume of the antenna, an extremely broadband frequency reconfigurable handset antenna is introduced [II]. The structure consists of frequency tunable antennas with MIMO capability. Each antenna has 60% smaller area compared to the already compact hybrid antenna introduced in [I]. It also outperforms the hybrid antenna in terms of hand losses due to its smaller antenna area. In addition, frequency tuning is used to compensate the impedance detuning. Both antennas perform very well compared to their competitors with respect to antenna volume, bandwidth and efficiency.

The PCB or chassis of the handset is a significant radiator, especially at the low-band (698–960 MHz). Hence, the user has a substantial effect on the antenna performance. This thesis presents the first analysis on the feasibility of balanced antennas for mobile handsets [VII]. The balanced antennas are not using the chassis on purpose and thus the user effect can be reduced. However, an effective frequency tuning method is required or the operation has to be limited above 2 GHz frequencies. Further research revealed that a combination of balanced and unbalanced (BUB) antennas can offer superior properties compared to traditional unbalanced antennas [III].

The handsets should comply with radiation safety limits and simultaneously have good radiation properties, for example, low power consumption. This thesis also presents different methods for reducing the electromagnetic exposure and the interaction between the user and handset. The shielded handset antenna is shown to significantly improve the SAR performance in the hand and head [V,VI]. The shielding can decrease the SAR by 81% compared to a traditional antenna. It is also ahown that the shielded antenna can improve the radiation efficiency in these cases, and consequently the link quality and the battery lifetime are improved as well. Different methods to control the reactive near-fields of the handsets are studied in [VIII]. It is shown that the quarter-wavelength wavetrap can be used to modify the chassis wavemodes in such a way that the field values in the open end of the chassis can be decreased significantly.

This work presents several methods and ideas that can be used when designing antennas for future handsets. It is also shown that a huge improvement of the antenna performance with the user is very challenging to obtain; one can always have a grip that, for instance, covers the antenna element and severely affects the antenna properties. One solution is to use frequency tuning in order to achieve a compact antenna volume and a good robustness against user-originated losses. One way could also be to invent new methods to excite the chassis wavemodes in such a way that the impact of the user can be minimized regardless of the hand grip.

Future 5th generation mobile networks (5G) are still under development, but it seems that the peak data rate will be in the range of 1–5 Gbit/s. The easiest way to increase the data rate is to use larger channel bandwidth. However, the frequency spectrum is a limited natural resource, and thus it is expected that the channel bandwidths will not significantly expand beyond the current maximum of 100 MHz. The data rate can also be increased by improving the spectral efficiency, for example by increasing the number of antennas (even up to 8–10 may be required). However, this will require a high isolation (>15 dB) between the antennas. This is challenging with traditional antennas since also inherently unsuitable antenna placements have to be accepted in order to include all

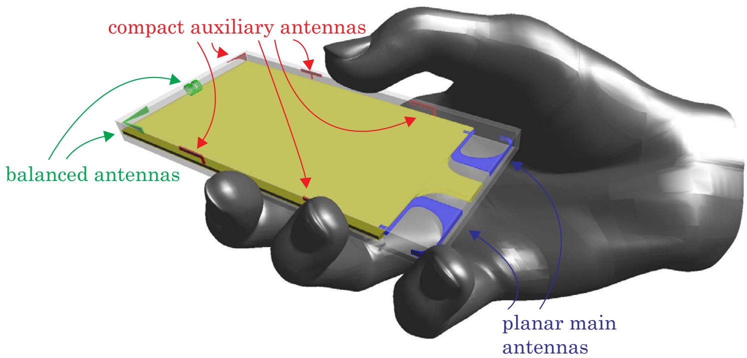


Figure 6.1. Possible scenario for a future 4G/5G handset. The antenna geometries and locations are only indicative.

the antennas within the handset. In addition, the operating frequencies used by future 5G mobile networks may go up to the 60 GHz range, where larger channel bandwidth is allowed. This will cause additional challenge for antenna designers.

One possible scenario for a future 4G/5G handset is shown in Figure 6.1. In this scenario, the handset features: *a*) multiple compact auxiliary antennas located around the handset in order to increase the probability that the user's hand is not covering the antenna and to enhance the data rate, *b*) planar and fairly compact main antennas that maximize the distance between the antenna and the user, *c*) an effective MEMS-based frequency tuning technology to enable the use of compact antennas and to reduce the impedance detuning caused by the user, *d*) nonself-resonant-type antennas to achieve a wide frequency tuning range, and *e*) possibility to combine balanced and unbalanced-type antennas to obtain an excellent isolation between the antennas at frequencies above 2 GHz.

Bibliography

[1] *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz* (ANSI / IEEE C95.1-2005), IEEE Standards Coordinating Committee Std., 2006.

[2] D. Heberling and M. Geissler, “Trends on handset antennas,” in *Proceedings of the 29th European Microwave Conference*, vol. 1, Munich, Germany, 5–7 October 1999, pp. 131–134.

[3] P. Vainikainen, J. Holopainen, C. Icheln, O. Kivekäs, M. Kyrö, M. Mustonen, S. Ranvier, R. Valkonen, and J. Villanen, “More than 20 antenna elements in future mobile phones, threat or opportunity?” in *Proceedings of the 3rd European Conference on Antennas and Propagation, (EuCAP 2009)*, Berlin, Germany, 23–27 March 2009, pp. 2940–2943.

[4] Z. Ying, “Antennas in cellular phones for mobile communications,” *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2286–2296, July 2012.

[5] J. Madden, 16 cellular bands, 3 Wi-Fi bands, 1 handset - the complexity of the ’worldphone’, FierceWireless, 2013. [Online]. Available: http://www.fiercewireless.com/story/madden-16-cellular-bands-3-wi-fi-bands-1-handset-complexity-worldphone/2013-05-31ixzz33qKnJJxp (Cited November 4, 2014).

[6] Z. Hu, C. Song, J. Kelly, P. Hall, and P. Gardner, “Wide tunable dual-band reconfigurable antenna,” *Electronics Letters*, vol. 45, no. 22, pp. 1109–1110, October 2009.

[7] R. Valkonen, C. Luxey, J. Holopainen, C. Icheln, and P. Vainikainen, “Frequency-reconfigurable mobile terminal antenna with MEMS switches,” in *Proceedings of the 4th European Conference on Antennas and Propagation, (EuCAP 2010)*, Barcelona, Spain, 12–16 April 2010.

[8] Y. Li, Z. Zhang, J. Zheng, Z. Feng, and M. Iskander, “A compact hepta-band loop-inverted F reconfigurable antenna for mobile phone,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 1, pp. 389–392, January 2012.

[9] D. Manteuffel and M. Arnold, “Considerations for reconfigurable multi-standard antennas for mobile terminals,” in *Proceedings of the International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials, (iWAT 2008)*, Chiba, Japan, 4–6 March 2008, pp. 231–234.

[10] J. Ollikainen, O. Kivekäs, and P. Vainikainen, “Low-loss tuning circuits for frequency-tunable small resonant antennas,” in *Proceedings of the 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC 2002)*, vol. 4, Lisbon, Portugal, 15–18 September 2002, pp. 1882–1887.

[11] R. Mansour, “RF MEMS-CMOS device integration: An overview of the potential for RF researchers,” *IEEE Microwave Magazine*, vol. 14, no. 1, pp. 39–56, January 2013.

[12] O. Kivekäs, 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, February 2004.

[13] M. Martinez-Vazquez, M. Geissler, and D. Heberling, “Volume considerations in the design of dual-band handset antennas,” in *Proceedings of the IEEE Antennas and Propagation Society International Symposium, (AP-S 2001)*, vol. 2, Boston, USA, 8–13 July 2001, pp. 112–115.

[14] C. A. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed. New York: John Wiley & Sons, 1997.

[15] J. D. Kraus, *Antennas for all applications*, 3rd ed. New York: McGraw-Hill Companies, 2002.

[16] H. A. Wheeler, “Fundamental limitations of small antennas,” *Proceedings of the IRE*, vol. 35, pp. 1479–1484, December 1947.

[17] J. Holopainen, “Compact UHF-band antennas for mobile terminals: Focus on modelling, implementation, and user interaction,” Ph.D. dissertation, Aalto University, Department of Radio Science and Engineering, Espoo, Finland, April 2011. [Online]. Available: http://lib.tkk.fi/Diss/2011/isbn9789526040868/

[18] J. Anguera, A. Andújar, and C. García, “Multiband and small coplanar antenna system for wireless handheld devices,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 7, pp. 3782–3789, July 2013.

[19] C. Rowell and E. Lam, “Mobile-phone antenna design,” *IEEE Antennas and Propagation Magazine*, vol. 54, no. 4, pp. 14–34, August 2012.

[20] R. Valkonen, M. Kaltiokallio, and C. Icheln, “Capacitive coupling element antennas for multi-standard mobile handsets,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 5, pp. 2783–2791, May 2013.

[21] J. Holopainen, J. Ilvonen, R. Valkonen, A. A. H. Azremi, and P. Vainikainen, “Study on the minimum required size of the low-band cellular antenna in variable-sized mobile terminals,” in *Proceedings of the 6th European Conference on Antennas and Propagation (EUCAP 2012)*, Prague, Czech Republic, 26–30 March 2012, pp. 2754–2758.

[22] F.-H. Chu and K.-L. Wong, “On-board small-size printed LTE/WWAN mobile handset antenna closely integrated with system ground plane,” *Microwave and Optical Technology Letters*, vol. 53, no. 6, pp. 1336–1343, June 2011.

[23] K.-L. Wong, T.-W. Kang, and M.-F. Tu, "Internal mobile phone antenna array for LTE/WWAN and LTE MIMO operations," *Microwave and Optical Technology Letters*, vol. 53, no. 7, pp. 1569–1573, July 2011.

[24] P. Vainikainen, J. Ollikainen, O. Kivekäs, and I. Kelander, "Resonator-based analysis of the combination of mobile handset antenna and chassis," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 10, pp. 1433–1444, October 2002.

[25] J. Holopainen, R. Valkonen, O. Kivekäs, J. Ilvonen, and P. Vainikainen, "Broadband equivalent circuit model for capacitive coupling element-based mobile terminal antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 716–719, 2010.

[26] J. Villanen, J. Ollikainen, O. Kivekäs, and P. Vainikainen, "Coupling element based mobile terminal antenna structures," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 7, pp. 2142–2153, July 2006.

[27] R. Valkonen, J. Ilvonen, K. Rasilainen, J. Holopainen, C. Icheln, and P. Vainikainen, "Avoiding the interaction between hand and capacitive coupling element based mobile terminal antenna," in *Proceedings of the 5th European Conference on Antennas and Propagation, (EUCAP 2011)*, Rome, Italy, 11–15 April 2011, pp. 2781–2785.

[28] R. Valkonen, J. Ilvonen, and P. Vainikainen, "Naturally non-selective handset antennas with good robustness against impedance mistuning," in *Proceedings of the 6th European Conference on Antennas and Propagation, (EUCAP 2012)*, Prague, Czech Republic, 26–30 March 2012.

[29] R. Valkonen, A. Lehtovuori, and D. Manteuffel, "Capacitive coupling elements - changing the way of designing antennas," in *Proceedings of the 8th European Conference on Antennas and Propagation, (EUCAP 2014)*, The Hague, The Netherlands, 6–11 April 2014, pp. 209–213.

[30] R. Valkonen, "Impedance matching and tuning of non-resonant mobile terminal antennas," Ph.D. dissertation, Aalto University, Department of Radio Science and Engineering, Espoo, Finland, March 2013. [Online]. Available: http://lib.tkk.fi/Diss/2013/isbn9789526050539/isbn9789526050539.pdf

[31] J. Holopainen, R. Valkonen, O. Kivekäs, J. Ilvonen, L. Martínez, P. Vainikainen, J. R. Kelly, and P. S. Hall, "Equivalent circuit model-based approach on the user body effect of a mobile terminal antenna," in *Proceedings of the Loughborough Antennas and Propagation Conference, (LAPC 2010)*, Loughborough, U.K., 8–9 November 2010, pp. 217–220.

[32] W. Yu, S. Yang, C.-L. Tang, and D. Tu, "Accurate simulation of the radiation performance of a mobile slide phone in a hand-head position," *IEEE Antennas and Propagation Magazine*, vol. 52, no. 2, pp. 168–177, April 2010.

[33] P. Futter, N. Chavannes, R. Tay, M. Meili, A. Klingenbock, K. Pokovic, and N. Kuster, "Reliable prediction of mobile phone performance for realistic in-use conditions using the FDTD method," *IEEE Antennas and Propagation Magazine*, vol. 50, no. 1, pp. 87–96, February 2008.

[34] N. Chavannes, R. Tay, N. Nikoloski, and N. Kuster, "Suitability of FDTD-based CAD tools RF design of mobile phones," *IEEE Antennas and Propagation Magazine*, vol. 45, no. 6, pp. 52–66, December 2003.

[35] J. Holopainen, O. Kivekäs, J. Ilvonen, R. Valkonen, C. Icheln, and P. Vainikainen, "Effect of the user's hands on the operation of lower UHF-band mobile terminal antennas: Focus on digital television receiver," *IEEE Transactions on Electromagnetic Compatibility*, vol. 53, no. 3, pp. 831–841, August 2011.

[36] A. Andújar, J. Anguera, and C. Puente, "Ground plane boosters as a compact antenna technology for wireless handheld devices," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 5, pp. 1668–1677, May 2011.

[37] J. Ollikainen, O. Kivekäs, A. Toropainen, and P. Vainikainen, "Internal dual-band patch antenna for mobile phones," in *Proceedings of the Millennium Conference on Antennas and Propagation, (AP2000)*, Davos, Switzerland, 9–14 April 2000.

[38] P. Vainikainen, "Antennas for terrestial mobile communications systems," in *Antennas for All Applications*, 3rd ed., J. D. Kraus, Ed. New York: Mc Graw Hill, 2002, p. 938.

[39] S. Saario, D. Thiel, J. Lu, and S. O'Keefe, "An assessment of cable radiation effects on mobile communications antenna measurements," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, vol. 1, Montreal, Canada, 16–18 July 1997, pp. 550–553.

[40] C. Icheln, J. Krogerus, and P. Vainikainen, "Use of balun chokes in small-antenna radiation measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 53, no. 2, pp. 498–506, April 2004.

[41] T. A. Laitinen, J. Toivanen, C. Icheln, and P. Vainikainen, "Spherical measurement system for determination of complex radiation patterns of mobile terminals," *Electronics Letters*, vol. 40, no. 22, pp. 1392–1394, October 2004.

[42] T. Laitinen, S. Ranvier, J. Toivanen, J. Ilvonen, L. Nyberg, J. Krogerus, C. Icheln, and P. Vainikainen, "Research activities on small antenna measurements at helsinki university of technology," in *Proceedings of the IEEE International Workshop on Antenna Technology, (iWAT 2009)*, Santa Monica, USA, 2–4 March 2009.

[43] C. Icheln, J. Ollikainen, and P. Vainikainen, "Effects of RF absorbers on measurements of small antennas in small anechoic chambers," *IEEE Aerospace and Electronic Systems Magazine*, vol. 16, no. 11, pp. 17–20, November 2001.

[44] C. Icheln, "Methods for measuring RF radiation properties of small antennas," Ph.D. dissertation, Helsinki University of Technology, Department of Radio Science and Engineering, Espoo, Finland, November 2001. [Online]. Available: http://lib.tkk.fi/Diss/2001/isbn9512256886/

[45] J. Holopainen, O. Kivekäs, J. Ilvonen, R. Valkonen, C. Icheln, and P. Vainikainen, “Effect of the user’s hands on the operation of lower UHF-band mobile terminal antennas: Focus on digital television receiver,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 53, no. 3, pp. 831–841, August 2011.

[46] SEMCAD-X, an FDTD-based electromagnetic simulator, version 14.6.2 Aletsch, Schmid & Partner Engineering AG, Zürich, Switzerland. [Online]. Available: http://www.speag.com/ (Cited November 4, 2014).

[47] IE3D, a MoM-based electromagnetic simulator, version 14.10, Mentor Graphics, Oregon, USA. [Online]. Available: http://www.mentor.com/ (Cited November 4, 2014).

[48] AWR Design Environment, a circuit simulator, version 9.06r, AWR Corporation, California, USA. [Online]. Available: http://www.awrcorp.com/ (Cited November 4, 2014).

[49] Optenni Lab, matching circuit generation and antenna analysis software, Optenni Ltd, Espoo, Finland. [Online]. Available: http://www.optenni.com/ (Cited November 4, 2014).

[50] 3GPP, Long Term Evolution. [Online]. Available: http://www.3gpp.org/ (Cited November 4, 2014).

[51] O. Kivekäs, J. Ollikainen, and P. Vainikainen, “Wideband dielectric resonator antenna for mobile phones,” *Microwave and Optical Technology Letters*, vol. 36, no. 1, pp. 25–26, January 2003.

[52] F.-H. Chu and K.-L. Wong, “Internal coupled-fed dual-loop antenna integrated with a USB connector for WWAN/LTE mobile handset,” *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 11, pp. 4215–4221, November 2011.

[53] Y.-J. Ren, “Ceramic based small LTE MIMO handset antenna,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 2, pp. 934–938, February 2013.

[54] I. Dioum, A. Diallo, S. Farssi, and C. Luxey, “A novel compact dual-band LTE antenna-system for MIMO operation,” *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 4, pp. 2291–2296, April 2014.

[55] J.-H. Lu and J.-L. Guo, “Small-size octaband monopole antenna in an LTE/WWAN mobile phone,” *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 548–551, 2014.

[56] R. Valkonen, J. Ilvonen, C. Icheln, and P. Vainikainen, “Inherently non-resonant multi-band mobile terminal antenna,” *Electronics Letters*, vol. 49, no. 1, pp. 11–13, January 2013.

[57] R. Valkonen and J. Ilvonen, “Multi-band antenna for wireless communication,” U.S. Patent Application US2 014 085 160 (A1), September 21, 2012. [Online]. Available: http://www.google.com/patents/US20140085160

[58] A. Lehtovuori, R. Valkonen, and J. Ilvonen, “On designing dual-band matching circuits for capacitive coupling element antennas,” in *Proceedings of the 8th European Conference on Antennas and Propagation, (EUCAP 2014)*, The Hague, The Netherlands, 6–11 April 2014, pp. 3909–3913.

[59] ——, “Designing capacitive coupling element antennas with bandwidth estimators,” *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 959–962, 2014.

[60] K. Fujimoto and J. R. James, *Mobile antenna systems handbook, 2nd edition*. Artech House, 2001.

[61] M. Parkkila, “*Study on mutual coupling in mobile multiantenna device*,” Master’s thesis, Aalto University School of Electrical Engineering, Department of Radio Science and Engineering, Espoo, Finland, 2012.

[62] J. Ollikainen, “Design and implementation techniques of wideband mobile communication antennas,” Ph.D. dissertation, Helsinki University of Technology, Department of Electrical and Communications Engineering, Espoo, Finland, November 2004. [Online]. Available: http://lib.tkk.fi/Diss/2004/isbn9512273810/

[63] J. Villanen and P. Vainikainen, “Optimum dual-resonant impedance matching of coupling element based mobile terminal antenna structures,” *Microwave and Optical Technology Letters*, vol. 49, no. 10, pp. 2472–2477, October 2007.

[64] H. Pues and A. Van de Capelle, “An impedance-matching technique for increasing the bandwidth of microstrip antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 11, pp. 1345–1354, November 1989.

[65] O. Kivekäs, “Design of high-efficiency antennas for mobile communications devices,” Ph.D. dissertation, Helsinki University of Technology, Department of Electrical and Communications Engineering, Espoo, Finland, August 2005. [Online]. Available: http://lib.tkk.fi/Diss/2005/isbn9512277581/

[66] S. Del Barrio, P. Bahramzy, S. Svendsen, O. Jagielski, and G. Pedersen, “Thermal loss in high-Q antennas,” *Electronics Letters*, vol. 50, no. 13, pp. 917–919, June 2014.

[67] O. Alrabadi, A. Tatomirescu, M. Knudsen, M. Pelosi, and G. Pedersen, “Breaking the transmitter-receiver isolation barrier in mobile handsets with spatial duplexing,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 2241–2251, April 2013.

[68] R. Valkonen, J. Holopainen, C. Icheln, and P. Vainikainen, “Broadband tuning of mobile terminal antennas,” in *Proceedings of the 2nd European Conference on Antennas and Propagation, (EuCAP 2007)*, Edinburgh, U.K., 11–16 November 2007, pp. 1–6.

[69] S. Caporal Del Barrio, A. Tatomirescu, G. Pedersen, and A. Morris, “Novel architecture for LTE world-phones,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1676–1679, 2013.

[70] Y. Chen, R. Martens, R. Valkonen, and D. Manteuffel, “A varactor-based tunable matching network for a non-resonant mobile terminal antenna,” in *Proceedings of the 8th European Conference on Antennas and Propagation, (EUCAP 2014)*, The Hague, The Netherlands, 6–11 April 2014, pp. 2225–2229.

[71] L. Liu, J. Rigelsford, and R. Langley, “Tunable multiband handset antenna operating at VHF and UHF bands,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 7, pp. 3790–3796, July 2013.

[72] R. Kuonanoja, “Low correlation handset antenna configuration for LTE MIMO applications,” in *Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI 2010)*, Toronto, Canada, 11–17 July 2010.

[73] K. Payandehjoo and R. Abhari, “Compact multi-band PIFAs on a semi-populated mobile handset with tunable isolation,” *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4814–4819, September 2013.

[74] L. Zidong, K. Boyle, J. Krogerus, M. De Jongh, K. Reimann, R. Kaunisto, and J. Ollikainen, “MEMS-switched, frequency-tunable hybrid slot/PIFA antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 311–314, 2009.

[75] G. Wang, *RF MEMS switches with novel materials and micromachining techniques for Soc/SoP RF front ends*. Ph.D. Dissertation, Atlanta, Georgia Institute of Technology, 2006.

[76] P. Grant and M. Denhoff, “A comparison between RF MEMS switches and semiconductor switches,” in *Proceedings of the International Conference on MEMS, NANO and Smart Systems, (ICMENS04)*, Alberta, Canada, 25–27 August 2004, pp. 515–521.

[77] WiSpry, Tunable Digital Capacitor Arrays, WiSpry inc., Irvine, USA. [Online]. Available: http://www.wispry.com/products-capacitors.php/ (Cited November 4, 2014).

[78] Radant, MEMS switches, Radant MEMS inc., Massachusetts, USA. [Online]. Available: http://www.radantmems.com/radantmems/ (Cited November 4, 2014).

[79] A. P. Lewis, M. Down, C. Chianrabutra, L. Jiang, S. Spearing, and J. McBride, “Lifetime testing of a developmental MEMS switch incorporating AU/MWCNT composite contacts,” in *Proceedings of the 27th International Conference on Electrical Contacts, (ICEC 2014)*, Frankfurt, Germany, 22–26 June 2014, pp. 1–6.

[80] J. Rahola, “Effect of antenna Q to the radiation efficiency of tunable antennas,” in *Proceedings of the 8th European Conference on Antennas and Propagation, (EUCAP 2014)*, The Hague, The Netherlands, 6–11 April 2014, pp. 3905–3908.

[81] ——, “Bandwidth potential and electromagnetic isolation: Tools for analysing the impedance behaviour of antenna systems,” in *Proceedings of the 3rd European Conference on Antennas and Propagation (EuCAP 2009)*, Berlin, Germany, 23–27 March 2009, pp. 944–948.

[82] Peregrine, Digitally Tunable Capacitors, Peregrine Semiconductor, San Diego, USA. [Online]. Available: http://www.psemi.com/content/products/product.php?product=PE64904/ (Cited November 4, 2014).

[83] P.-S. Kildal and K. Rosengren, "Correlation and capacity of MIMO systems and mutual coupling, radiation efficiency, and diversity gain of their antennas: simulations and measurements in a reverberation chamber," *IEEE Communications Magazine*, vol. 42, no. 12, pp. 104–112, December 2004.

[84] A. Cihangir, F. Ferrero, G. Jacquemod, P. Brachat, and C. Luxey, "Neutralized coupling elements for MIMO operation in 4G mobile terminals," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 141–144, 2014.

[85] S. Zhang, K. Zhao, Z. Ying, and S. He, "Adaptive quad-element multi-wideband antenna array for user-effective LTE MIMO mobile terminals," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 8, pp. 4275–4283, August 2013.

[86] A. Diallo, C. Luxey, P. Le Thuc, R. Staraj, and G. Kossiavas, "Study and reduction of the mutual coupling between two mobile phone PIFAs operating in the DCS1800 and UMTS bands," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 11, pp. 3063–3074, November 2006.

[87] C.-Y. Chiu, C.-H. Cheng, R. Murch, and C. Rowell, "Reduction of mutual coupling between closely-packed antenna elements," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 6, pp. 1732–1738, June 2007.

[88] I. Dioum, A. Diallo, C. Luxey, and S. Farsi, "Compact dual-band monopole antenna for LTE mobile phones," in *Proceedings of the Loughborough Antennas and Propagation Conference, (LAPC 2010)*, Loughborough, U.K., 8–9 November 2010, pp. 593–596.

[89] Y. Wang and Z. Du, "A wideband printed dual-antenna with three neutralization lines for mobile terminals," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 3, pp. 1495–1500, March 2014.

[90] H. Li, Z. Miers, and B. K. Lau, "Design of orthogonal MIMO handset antennas based on characteristic mode manipulation at frequency bands below 1 GHz," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 5, pp. 2756–2766, May 2014.

[91] S. Park and C. Jung, "Compact MIMO antenna with high isolation performance," *Electronics Letters*, vol. 46, no. 6, pp. 390–391, March 2010.

[92] H. Li, B. K. Lau, and S. He, "Angle and polarization diversity in compact dual-antenna terminals with chassis excitation," in *Proceedings of the XXXth General Assembly and Scientific Symposium, (URSI 2011)*, Istanbul, Turkey, 13–20 August 2011.

[93] R. Martens, J. Holopainen, E. Safin, J. Ilvonen, and D. Manteuffel, "Optimal dual-antenna design in a small terminal multiantenna system," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1700–1703, 2013.

[94] K. Ogawa, T. Matsuyoshi, and K. Monma, "An analysis of the performance of a handset diversity antenna influenced by head, hand, and shoulder effects at 900 MHz: Part II–correlation characteristics," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 3, pp. 845–853, May 2001.

[95] T. Taga, "Analysis for mean effective gain of mobile antennas in land mobile radio environments," *IEEE Transactions on Vehicular Technology*, vol. 39, no. 2, pp. 117–131, May 1990.

[96] R. Vaughan and J. Andersen, "Antenna diversity in mobile communications," *IEEE Transactions on Vehicular Technology*, vol. 36, no. 4, pp. 149–172, November 1987.

[97] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, March 1998.

[98] E. Tiirola and J. Ylitalo, "Comparison of beamforming and diversity approaches for the coverage extension of wcdma macro cells," in *Proceedings of the IEEE Vehicular Technology Conference, (VTC 2001 Spring)*, vol. 3, Rhodes, Greece, 6–9 May 2001, pp. 1274–1278.

[99] A. A. H. Azremi, M. Kyrö, J. Ilvonen, J. Holopainen, S. Ranvier, C. Icheln, and P. Vainikainen, "Five-element inverted-F antenna array for MIMO communications and radio direction finding on mobile terminal," in *Proceedings of the Loughborough Antennas and Propagation Conference, (LAPC 2009)*, Loughborough, U.K., 16–17 November 2009, pp. 557–560.

[100] S. Zhang, K. Zhao, Z. Ying, and S. He, "Diagonal antenna-chassis mode for wideband LTE MIMO antenna arrays in mobile handsets," in *Proceedings of the International Workshop on Antenna Technology (iWAT 2013)*, Karlsruhe, Germany, 4–6 March 2013, pp. 407–410.

[101] J. Rahola and J. Ollikainen, "Optimal antenna placement for mobile terminals using characteristic mode analysis," in *Proceedings of the 1st European Conference on Antennas and Propagation, (EuCAP 2006)*, Nice, France, 6–10 November 2006.

[102] J. Toftgard, S. N. Hornsleth, and J. B. Andersen, "Effects on portable antennas of the presence of a person," *IEEE Transactions on Antennas and Propagation*, vol. 41, no. 6, pp. 739–746, June 1993.

[103] K. R. Boyle, Y. Yuan, and L. P. Ligthart, "Analysis of mobile phone antenna impedance variations with user proximity," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 2, pp. 364–372, February 2007.

[104] R. Valkonen, S. Myllymäki, A. Huttunen, J. Holopainen, J. Ilvonen, P. Vainikainen, and H. Jantunen, "Compensation of finger effect on a mobile terminal antenna by antenna selection," in *Proceedings of the 12th International Conference on Electromagnetics in Advanced Applications, (ICEAA'10)*, Sydney, Australia, 20–24 September 2010, pp. 364–367.

[105] M. Pelosi, O. Franek, M. B. Knudsen, and G. F. Pedersen, "Influence of dielectric loading on PIFA antennas in close proximity to user's body," *Electronics Letters*, vol. 45, no. 5, pp. 246–248, February 2009.

[106] J. Anguera, A. Andújar, A. Camps, C. Puente, and C. Picher, "Mitigation of the finger loading effect in handset antennas," in *Proceedings of the 4th European Conference on Antennas and Propagation, (EuCAP 2010)*, Barcelona, Spain, 12–16 April 2010.

[107] L. Chung-Huan, E. Ofli, N. Chavannes, E. Cherubini, H. U. Gerber, and N. Kuster, "Effects of hand phantom on mobile phone antenna performance," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 9, pp. 2763–2770, July 2009.

[108] J. Poutanen, J. Villanen, C. Icheln, and P. Vainikainen, "Behavior of mobile terminal antennas near human tissue at a wide frequency range," in *Proceedings of the International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials, (iWAT 2008)*, Keyaki-kaikan, Japan, 4–6 March 2008, pp. 219–222.

[109] M. A. Mellah, A. Sibille, C. Roblin, M. Nedil, and T. A. Denidni, "Statistical modeling of the "antenna-head" interaction," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 454–457, 2011.

[110] A. Hadjem, E. Conil, A. Gati, Man-Fai, Wong, and J. Wiart, "Analysis of power absorbed by children's head as a result of new usages of mobile phone," *IEEE Transactions on Electromagnetic Compatibility*, vol. 52, no. 4, pp. 812–819, November 2010.

[111] A.-K. Lee and J. Yun, "A comparison of specific absorption rates in sam phantom and child head models at 835 and 1900 MHz," *IEEE Transactions on Electromagnetic Compatibility*, vol. 53, no. 3, pp. 619–627, August 2011.

[112] K. Zhao, S. Zhang, Z. Ying, T. Bolin, and S. He, "SAR study of different MIMO antenna designs for LTE application in smart mobile handsets," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 6, pp. 3270–3279, June 2013.

[113] J.-O. Mattsson and L. de Leon, "SAR evaluation of a multi-antenna system," in *Proceedings of the IEEE Antennas and Propagation Society International Symposium, (AP-S 2007)*, Honolulu, USA, 10–15 June 2007, pp. 1373–1376.

[114] J. Krogerus, J. Toivanen, C. Icheln, and P. Vainikainen, "Effect of the human body on total radiated power and the 3-D radiation pattern of mobile handsets," *IEEE Transactions on Instrumentation and Measurement*, vol. 53, no. 6, pp. 2375–2385, December 2007.

[115] M. Pelosi and G. Pedersen, "Impact of tolerances in dielectric properties of hand phantoms," *Electronics Letters*, vol. 46, no. 3, pp. 193–194, February 2010.

[116] M. Pelosi, O. Franek, M. Knudsen, G. Pedersen, and J. Andersen, "Antenna proximity effects for talk and data modes in mobile phones," *IEEE Antennas and Propagation Magazine*, vol. 52, no. 3, pp. 15–27, June 2010.

[117] M. Pelosi, O. Franek, M. B. Knudsen, M. Christensen, and G. F. Pedersen, "A grip study for talk and data modes in mobile phones," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 856–865, April 2009.

[118] A. A. H. Azremi, J. Ilvonen, R. Valkonen, J. Holopainen, O. Kivekäs, C. Icheln, and P. Vainikainen, "Coupling element-based dual-antenna structures for mobile terminal with hand effects," *International Journal of Wireless Information Networks*, vol. 18, no. 3, pp. 146–157, June 2011.

[119] P. Hui, “Positive hand effect on mobilte handset antennas,” in *Proceedings of the Asia-Pacific Microwave Conference, (*APMC 2008), Macau, 16–20 December 2008.

[120] IEEE, *IEEE Standard Definitions of Terms for Antennas*. IEEE STD-145, March 1993.

[121] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*, 2nd ed. New York: John Wiley & Sons, 2001.

[122] C. Famdie, W. Schroeder, and K. Solbach, “Optimal antenna location on mobile phones chassis based on the numerical analysis of characteristic modes,” in *Proceedings of the European Microwave Conference, (EUMC 2007).*, Munich, Germany, 9–12 October 2007, pp. 987–990.

[123] R. F. Harrington and J. Mautz, “Theory of characteristic modes for conducting bodies,” *IEEE Transactions on Antennas and Propagation*, vol. 19, no. 5, pp. 622–628, September 1971.

[124] D. M. Pozar, *Microwave Engineering*, 4th ed. John Wiley & Sons, 2012.

[125] A. D. Yaghjian and S. R. Best, “Impedance, bandwidth, and Q of antennas,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 4, pp. 1298–1324, April 2005.

[126] J. Heiskanen, “*Antenna design for a metal-cover mobile phone*,” Master’s thesis, Aalto University School of Electrical Engineering, Department of Radio Science and Engineering, Espoo, Finland, May 2011.

[127] W. N. Allen and D. Peroulis, “Bandwidth-optimal single-tunable-element matching network for antenna tuning in mobile handsets,” in *IEEE Microwave Symposium Digest, (MTT 2011)*, Baltimore, USA, 5–10 June 2011.

[128] G. Pedersen, “Mobile phone antenna performance 2013,” *Aalborg University, Report*, pp. 1–14, November 2013. [Online]. Available: http://vbn.aau.dk/files/168617784/MobilephoneTest2013Ver2_2_4_.pdf

[129] *Test Plan for Wireless Device Over-the-Air Performance*, CTIA, Tech. Rep., Revision 3.0 Std., April 2009.

[130] M. Komulainen, M. Berg, H. Jantunen, E. Salonen, and C. Free, “A frequency tuning method for a planar inverted-F antenna,” *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 4, pp. 944–950, April 2008.

[131] K. Boyle, T. Bakker, M. de Jongh, and A. van Bezooijen, “Real-time adaptation of mobile antenna impedance matching,” in *Proceedings of the Loughborough Antennas and Propagation Conference, (LAPC 2010)*, Loughborough, U.K., 8–9 November 2010, pp. 22–25.

[132] K. Boyle, E. Spits, M. A. de Jongh, S. Sato, T. Bakker, and A. van Bezooijen, “A self-contained adaptive antenna tuner for mobile phones,” in *Proceedings of the 6th European Conference on Antennas and Propagation, (EUCAP 2012)*, Prague, Czech Republic, 26–30 March 2012.

[133] K. Boyle, E. Spits, M. de Jongh, S. Sato, T. Bakker, and A. van Bezooijen, “Antenna tuning for mobile devices: The state of the art and some glimpses of the future,” in *Proceedings of the Loughborough Antennas and Propagation Conference, (LAPC 2012)*, Loughborough, UK, 12–13 November 2012.

[134] K. Boyle, E. Spits, M. De Jongh, S. Sato, T. Bakker, and A. van Bezooijen, “Gain statistics for mobile phone antenna tuners,” in *Proceedings of the 7th European Conference on Antennas and Propagation (EUCAP 2013)*, Gothenburg, Sweden, 8–12 April 2013, pp. 432–436.

[135] Y. Okada, M. Yamamoto, and T. Nojima, “Unbalanced fed dipole antenna mounted on ground plane with L-shaped parasitic elements for mobile handsets,” in *Proceedings of the International Symposium on Antennas and Propagation, (ISAP 2008)*, Taipei, Taiwan, 27–30 October 2008, paper 1645395.

[136] C.-H. Li, E. Ofli, N. Chavannes, and N. Kuster, “The effects of hand phantom on mobile phone antenna ota performance,” in *Proceedings of the 2nd European Conference on Antennas and Propagation, (EuCAP 2007)*, Edinburgh, U.K., 11–16 November 2007.

[137] C.-H. Li, E. Ofli, N. Chavannes, E. Cherubini, H. Gerber, and N. Kuster, “Effects of hand phantom and different use patterns on mobile phone antenna radiation performance,” in *Proceedings of the IEEE Antennas and Propagation Society, (AP-S 2008)*, San Diego, USA, 5–11 July 2008.

[138] M. Berg, M. Sonkki, and E. Salonen, “Experimental study of hand and head effects to mobile phone antenna radiation properties,” in *Proceedings of the 3rd European Conference on Antennas and Propagation, (EuCAP 2009)*, Berlin, Germany, 23–27 March 2009, pp. 437–440.

[139] M. Foegelle, K. Li, A. Pavacic, and P. Moller, ”Developing a Standard Hand Phantom for Wireless Testing,” Wireless Design and Development, 2008. [Online]. Available: http://www.wirelessdesignmag.com/articles/2008/11/developing-standard-hand-phantom-wireless-testing/ (Cited November 4, 2014).

[140] J. Ilvonen, K. Rasilainen, R. Valkonen, J. Holopainen, J. Krogerus, and V. Viikari, “Extension to characterization model for GPS antenna performance in mobile terminals,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1212–1215, 2013.

[141] W.-J. Liao, J.-T. Yeh, and S.-H. Chang, “Circularly polarized chip antenna design for GPS reception on handsets,” *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 7, pp. 3482–3489, July 2014.

[142] R. F. Harrington, “Effect of antenna size on gain, bandwidth, and efficiency,” *The Journal of Research of the National Institute of Standards*–D. *radio propagation*, vol. 64D, no. 1, pp. 1–12, January-February 1960.

[143] R. Hansen, “Fundamental limitations in antennas,” *Proceedings of the IEEE*, vol. 69, no. 2, pp. 170–182, February 1981.

[144] M. Berg and E. Salonen, “Control system for compensation of antenna mistuning and absorption caused by user’s index finger,” in *Proceedings of the 4th European Conference on Antennas and Propagation, (EuCAP 2010)*, Barcelona, Spain, 12–16 April 2010.

[145] S. Caporal Del Barrio, A. Tatomirescu, G. Pedersen, and A. Morris, “Antenna miniaturization with MEMS tunable capacitors: Techniques and trade-offs,” *International Journal of Antennas and Propagation*, vol. 2014, p. 8, July 2014.

[146] L. Zheng and D. Tse, “Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels,” *IEEE Transactions on Information Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[147] E. Stauffer, O. Oyman, R. Narasimhan, and A. Paulraj, “Finite-SNR diversity-multiplexing tradeoffs in fading relay channels,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 2, pp. 245–257, February 2007.

[148] A. A. H. Azremi, “Multi-element antennas for mobile communication systems: Design, evaluation and user interactions,” Ph.D. dissertation, Aalto University, Department of Radio Science and Engineering, Espoo, Finland, November 2013. [Online]. Available: http://lib.tkk.fi/Diss/2013/isbn9789526053394/isbn9789526053394.pdf

[149] A. A. H. Azremi, J. Ilvonen, C. Li, J. Holopainen, and P. Vainikainen, “Influence of the user’s hand on mutual coupling of dual-antenna structures on mobile terminal,” in *Proceedings of the 6th European Conference on Antennas and Propagation, (EUCAP 2012)*, Prague, Czech Republic, 26–30 March 2012, pp. 1222–1226.

[150] A. A. H. Azremi, K. Haneda, and P. Vainikainen, “Site-specific evaluation of a MIMO channel capacity for multi-antenna mobile terminals in proximity to a human hand,” in *Proceedings of the 5th European Conference on Antennas and Propagation, (EUCAP 2011)*, Rome, Italy, 11–15 April 2011, pp. 538–542.

[151] A. A. H. Azremi, J. Ilvonen, R. Valkonen, and V. Viikari, “Eight-element antenna array for diversity and MIMO mobile terminal in LTE 3500 mhz band,” *Microwave and Optical Technology Letters*, vol. 56, no. 6, pp. 1323–1327, June 2014.

[152] R. Tian, B. K. Lau, and Z. Ying, “Multiplexing efficiency of MIMO antennas with user effects,” in *Proceedings of the IEEE Antennas and Propagation Society International Symposium (APSURSI 2012)*, 8–14 July 2012, pp. 1–2.

[153] ——, “Multiplexing efficiency of MIMO antennas,” *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 183–186, 2011.

[154] ——, “Multiplexing efficiency of MIMO antennas in arbitrary propagation scenarios,” in *Proceedings of the 6th European Conference on Antennas and Propagation, (EUCAP 2012)*, Prague, Czech Republic, 26–30 March 2012, pp. 373–377.

[155] P. S. Kildal and K. Rosengren, “Electromagnetic analysis of effective and apparent diversity gain of two parallel dipoles,” *IEEE Antennas and Wireless Propagation Letters*, vol. 2, no. 1, pp. 9–13, 2003.

[156] V. Plicanic, B. K. Lau, A. Derneryd, and Z. Ying, “Actual diversity performance of a multiband diversity antenna with hand and head effects,” *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 5, pp. 1547–1556, May 2009.

[157] P.-S. Kildal, K. Rosengren, J. Byun, and J. Lee, “Definition of effective diversity gain and how to measure it in a reverberation chamber,” *Microwave and Optical Technology Letters*, vol. 34, no. 1, pp. 56–59, July 2002.

[158] K. Ogawa, A. Yamamoto, and J.-i. Takada, “Multipath performance of handset adaptive array antennas in the vicinity of a human operator,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2422–2436, August 2005.

[159] D. Yuan, Z. Du, K. Gong, and Z. Feng, “A four-element antenna system for mobile phones,” *IEEE Antennas and Wireless Propagation Letters*, vol. 6, pp. 655–658, 2007.

[160] A. A. H. Azremi, V. Papamichael, and P. Vainikainen, “Multi-antenna mobile terminal diversity performance in proximity to human hands under different propagation environment conditions,” *Electronics Letters*, vol. 47, no. 22, pp. 1214–1215, October 2011.

[161] A. Andújar, J. Anguera, Y. Cobo, and C. Picher, “Distributed antenna systems for wireless handheld devices robust to hand loading,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 10, pp. 4830–4837, October 2012.

[162] “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),” International Commission on Non-Ionizing Radiation Protection (ICNIRP), pp. 494–522, April 1998.

[163] P. Wainwright, “Thermal effects of radiation from cellular telephones,” *Physics in Medicine and Biology*, vol. 45, no. 8, pp. 2363–2372, August 2000.

[164] R. Nylund and D. Leszczynski, “Proteomics analysis of human endothelial cell line EA.hy926 after exposure to GSM 900 radiation,” *Proteomics*, pp. 1359–1365, March 2004.

[165] L. Salford, A. Brun, J. Eberhardt, L. Malmgren, and B. Persson, “Nerve cell damage in mammalian brain after exposure to microwaves from gsm mobile phones,” *Environmental Health Perspectives*, vol. 111, no. 7, pp. 881–883, January 2003.

[166] *Recommendation E.800: Definitions of terms related to quality of service*, International Telecommunication Union’s Telecommunication Standardization Sector (ITU-T) Std., 2008.

[167] M. Berg, M. Sonkki, S. Myllymäki, T. Tuovinen, and E. Salonen, “Effect of the mobile terminal antenna efficiency on the cellular network issues,” in *Proceedings of the 6th European Conference on Antennas and Propagation, (EUCAP 2012)*, Prague, Czech Republic, 26–30 March 2012.

[168] C.-H. Li, M. Douglas, E. Ofli, B. Derat, S. Gabriel, N. Chavannes, and N. Kuster, “Influence of the hand on the specific absorption rate in the head,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 1066–1074, February 2012.

[169] A. Sarolic, D. Senic, Z. Zivkovic, and A. Zorica, “Influence of human head and hand on PIFA antenna matching properties and SAR,” in *Proceedings of the 19th International Conference on Software, Telecommunications and Computer Networks, (SoftCOM)*, Adriatic Islands Split, Croatia, 15–17 September 2011.

[170] *American National Standard for Method of Measurements of Compatibility between Wireless Communication Devices and Hearing Aids* (ANSI C63.19-2007), American National Standards Institute Std., 2007.

[171] H. Arai, “Adaptive pattern controlled handset antenna by analog phase shifters,” in *Proceedings of the 3rd European Conference on Antennas and Propagation, (EuCAP 2009)*, Berlin, Germany, 23–27 March 2009, pp. 2536–2540.

[172] M. Krairiksh, “Development of a handset adaptive antenna using phased-array of switched-beam elements,” in *Proceedings of the International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials, (iWAT 2008)*, Keyaki-kaikan, Japan, 4–6 March 2008, pp. 87–90.

[173] F. Ferrero, A. Diallo, C. Luxey, and B. Derat, “Phased two-element PIFA for adaptative pattern in UMTS handsets,” in *Proceedings of the IEEE International Workshop on Antenna Technology, (iWAT 2009)*, Santa Monica, USA, 2–4 March 2009.

[174] J. Anguera, A. Andújar, Y. Cobo, C. Puente, and C. Picher, “Handset antenna array to mitigate the finger loading effect,” in *Proceedings of the 5th European Conference on Antennas and Propagation, (EUCAP 2011)*, Rome, Italy, 11–15 April 2011, pp. 611–614.

[175] J. Anguera, A. Camps, A. Andújar, and C. Puente, “Enhancing robustness of handset antennas to finger loading effects,” *Electronics Letters*, vol. 45, no. 15, pp. 770–771, July 2009.

[176] J. Moustafa, R. Abd-Alhameed, D. Zhou, C. H. See, N. McEwan, P. S. Excell, K. N. Ramli, and Z. Abidin, “SAR measurements for several two elements phased antenna array handsets,” in *Proceedings of the 3rd European Conference on Antennas and Propagation, (EuCAP 2009)*, Berlin, Germany, 23–27 March 2009, pp. 2201–2204.

[177] R. Abd-Alhameed, N. McEwan, P. Excell, and E. A. Abdulmula, “A two element phased array antenna for mobile handsets to reduce the mutual effect with the human head,” in *Proceedings of the IEE National Conference on Antennas and Propagation*, York, UK, 31 March – 1 April 1999, pp. 291–294.

[178] M. Mangoud, R. Abd-Alhameed, N. McEwan, P. Excell, and E. A. Abdulmula, “SAR reduction for handset with two-element phased array antenna computed using hybrid MoM/FDTD technique,” *Electronics Letters*, vol. 35, no. 20, pp. 1693–1694, September 1999.

[179] “SAR evaluation considerations for handsets with multiple transmitters and antennas,” Federal Communications Commission, Tech. Rep., 2012, kDB648474.

[180] K.-C. Chim, K. Chan, and R. Murch, “Investigating the impact of smart antennas on SAR,” *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 5, pp. 1370–1374, May 2004.

[181] K. Boyle and P. Steeneken, “A five-band reconfigurable PIFA for mobile phones,” *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 11, pp. 3300–3309, November 2007.

[182] R. Valkonen, J. Holopainen, C. Icheln, and P. Vainikainen, “Minimization of power loss and distortion in a tuning circuit for a mobile terminal antenna,” in *Proceedings of the International Symposium on Antennas and Propagation, (ISAP 2008)*, Taipei, Taiwan, 27–30 October 2008, pp. 449–452.

[183] O. Kivekäs, J. Ollikainen, and P. Vainikainen, “Frequency-tunable internal antenna for mobile phones,” in *Proceedings of the 12th International Symposium on Antennas, (JINA 2002)*, Nice, France, 12–14 November 2002, pp. 53–56.

[184] U. Shah, M. Sterner, and J. Oberhammer, “Analysis of linearity deterioration in multidevice RF MEMS circuits,” *IEEE Transactions on Electron Devices*, vol. 61, no. 5, pp. 1529–1535, May 2014.

[185] J. Ilvonen, “*Isolated antenna structures of mobile terminals*,” (Master’s thesis, Helsinki University of Technology, Department of Radio Science and Engineering, Espoo, Finland, August 2009.

[186] P. M. T. Ikonen and K. R. Boyle, “Analysis of cellular antennas for hearing-aid compatible mobile phones,” *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 1043–1052, February 2012.

[187] S. Hayashida, H. Morishita, and K. Fujimoto, “Self-balanced wideband folded loop antenna,” *IEEE Proceedings Microwaves, Antennas and Propagation*, vol. 153, no. 1, pp. 7–12, February 2006.

[188] K. Ishimiya and J.-I. Takada, “Multi-band folded dipole antenna for mobile phone,” in *International Workshop on Antenna Technology: Small and Smart Antennas Metamaterials and Applications, (IWAT ’07)*, Cambridge, U.K., 21–23 March 2007, pp. 275–278.

[189] A. Ikram, C. Beckman, and S. Irmscher, “Design and development of a multiband loop antenna for cellular mobile handsets,” in *International Workshop on Antenna Technology, (iWAT ’11)*, Hong Kong, 7–9 March 2011, pp. 251–254.

[190] F. Po, E. de Foucauld, D. Morche, P. Vincent, and E. Kerherve, “A novel method for synthesizing an automatic matching network and its control unit,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 58, no. 9, pp. 2225–2236, September 2011.

[191] M. Sager, M. Forcucci, and T. Kristensen, “A novel technique to increase the realized efficiency of a mobile phone antenna placed beside a head-phantom,” in *Proceedings of the IEEE Antennas and Propagation Society International Symposium*, vol. 2, Columbus, USA, 22–27 June 2003, pp. 1013–1016.

[192] P. Lindberg and E. Ojefors, “A bandwidth enhancement technique for mobile handset antennas using wavetraps,” *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 8, pp. 2226–2233, August 2006.

[193] Federal Communications Commission, requlatory requirements for Hearing Aid Compatibility (HAC). [Online]. Available: http://www.fcc.gov/encyclopedia/hearing-aid-compatibility-hac/ (Cited November 4, 2014).

[194] M. R. Islam and M. Ali, “Ground current modification of mobile terminal antennas and its effects,” *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 438–441, 2011.

[195] J. Anguera, A. Andújar, and C. Puente, “A mechanism to electrically enlarge the ground plane of handset antennas: A bandwidth enhancement technique,” *Microwave and Optical Technology Letters*, vol. 53, no. 7, pp. 1512–1517, July 2011.

Errata

Publication II

In Section 4.4, p. 241, Table 2, the units for the bandwidths of the main and aux antennas should be (GHz), not (%).

Publication VIII

In Conclusions, p. 595, ”...GMS1900...” should read ”...GSM1900...”.

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Requirements for mobile handsets are constantly increasing: the handset should be small in size, new services require higher data rates, the battery is supposed to last several days, and the handset should desirably operate anywhere in the world. Besides all these, the handset should have a good robustness against environmental changes caused for instance by the user's hand. How can all of these requirements be met? What are the challenges for antenna designers? This thesis contributes to answering these questions.

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