Adaptive Multiport Antennas for Handsets

Rasmus Luomaniemi
Adaptive Multiport Antennas for Handsets

Rasmus Luomaniemi

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Electrical Engineering, at a public examination held via a remote connection on 21 June 2021 at 16.

Aalto University
School of Electrical Engineering
Department of Electronics and Nanoengineering
Supervising professor
Assoc. Prof. Ville Viikari, Aalto University, Finland

Thesis advisor
Dr. Anu Lehtovuori, Aalto University, Finland

Preliminary examiners
Assist. Prof. Daniele Cavallo, Delft University of Technology, The Netherlands
Prof. Lars Jonsson, KTH Royal Institute of Technology, Sweden

Opponent
Assoc. Prof. Mohammad S. Sharawi, Polytechnique Montréal, Canada
Abstract
Generally, the main factors driving the evolution of modern handset antennas are the requirements for increasing the data capacity and the visual appearance restricting the volume of the antennas. To increase the data transfer rates, new bands with wider frequency ranges are used together with an increasing number of multiple-input multiple-output (MIMO) antennas. The appearance of the device is an important factor in the smartphone industry. However, nearby conductive objects, such as the screen or metal rim of the device, hinder the operation of the antennas. Therefore, new innovations and techniques are required to reach these difficult goals. This thesis studies whether multiport antenna techniques can be used to address the aforementioned challenges.

In the first part of this thesis, new design methods for multiport handset antennas are presented. The first method can be used to design switch-reconfigurable antenna systems. The rim is used for MIMO operation on different frequency bands with switches and the proposed design method makes the optimization process efficient. The proposed antennas achieve 30-40 % total efficiency in the 700-960 MHz band and 25-75 % total efficiency in the 1.7-2.7 GHz and 3.0-4.0 GHz bands. The second method utilizes multiport antennas and characteristic modes to utilize an unbroken metal rim for MIMO antennas. The proposed antennas achieve an efficiency of 15-59 % at low band and 25-80 % at higher bands.

The second part of this thesis focuses on the interaction between the user and multiport antennas. First, the effect of the user's hand on the operation of the antennas designed in the first part is investigated. Given the promising results obtained, the study is extended to include the user in the design process from the beginning. A design process for hand-immune antennas based on the characteristic modes of both the metallic antenna structure and lossy dielectrics of the user is presented. The resulting antennas achieve a total efficiency of more than 30 % at low band with the user holding the device.

A common problem even with multiport antennas is the ability to achieve a wide enough bandwidth. The third part of this thesis presents a method for realizing antennas in extremely small volumes inside smartphones by taking advantage of the gap between the battery and the back cover of the device. An average total efficiency of 35 % is achieved across the 3.3-4.2 GHz band with an antenna height of only 0.75 mm. Following that, a more general design tool for accelerating the design process of multiport antennas is presented. Using the quality factor combined with a proper choice of feeding signals, the achievable performance of a structure can be estimated without the need for time-consuming matching network optimization.

The new and computationally efficient design methods developed in this work enable the realization of antennas with improved performance. Moreover, the presented antenna designs demonstrate the benefits of multiport antennas in comparison to traditional solutions.

Keywords frequency-reconfigurable, mobile antennas, multiport antennas, user effect

ISDN (printed) 978-952-64-0366-3 ISBN (pdf) 978-952-64-0367-0
ISSN (printed) 1799-4934 ISSN (pdf) 1799-4942
Location of publisher Helsinki Location of printing Helsinki Year 2021
Tekijä
Rasmus Luomaniemi

Väitöskirjan nimi
Matkapuhelimen adaptiiviset moniporttiantennit

Julkaisija
Sähkötekniikan korkeaoulu

Yksikkö
Elektroniikan ja nanotekniikan laitos

Sarja
Aalto University publication series DOCTORAL DISSERTATIONS 63/2021

Tutkimusala
Radiotekniikka

Käsikirjoituksen pvm
01.02.2021

Väitöspäivä
21.06.2021

Väittelyluvan myöntämispäivä
14.04.2021

Kieli
Englanti

Monografia
Ykivalvot
Esseevähöstökirja

Tiivistelmä


Riittävän kaistanlevyden saavuttaminen on haaste myös moniporttiantenneille. Kolmannessa osassa esitetään menetelma, jolla voidaan toteuttaa antennen akun ja laitteen takakannen välissä olevaan erittäin pieneen raken. Vain 0.75 mm korkealla antennilla saavutetaan keskimäärin 35 %:n hyötyysuhde 3.3-4.2 GHz:n kaistalla. Lisäksi esitellään suunnittelutapoa, jonka avulla moniporttiantennien suunnitteluprosessi on oikealla tavalla määrättyjä syöttösignalateita, antennirakenteen suorituskykyä voidaan arvioida luotettavasti ilman että aikaa vievää sovituspiirien optimointia tarvitsee toista suurelle määrälle rakenteita.

Työssä kehitetut uudet ja laskennallisesti tehokkaat suunnittelumenetelmat mahdollistavat yhä suorituskykyisempimmin antennien suunnittelun. Esitetyn auttaa ymmärtää, että moniporttiantennitekniikalla voidaan saada merkittävää hyötyä perinteisissä menetelmissä verratuna.

Avainsanat
käyttäjän vaikutus, mobiiliantennit, moniporttiantennit, taajuussäädetettävyys

ISBN (painettu) 978-952-64-0366-3
ISBN (pdf) 978-952-64-0367-0
ISSN (painettu) 1799-4934
ISSN (pdf) 1799-4942
Julkaisupaikka Helsinki
Painopaikka Helsinki
Vuosi 2021
Sivumäärä 174

The work resulting in this doctoral thesis has been carried out in the Department of Electronics and Nanoengineering, Aalto University School of Electrical Engineering, in 2018–2021. This research has been funded by Business Finland, Nokia Bell Labs, Huawei Technologies Finland, RF360, Pulse Electronics Finland, and Sasken Finland. In addition, Aalto ELEC Doctoral School, Nokia Foundation, HPY Research Foundation, and the Finnish Foundation for Technology Promotion have supported my work.

First, I would like to thank my supervisor Prof. Ville Viikari for giving me the opportunity to work with these interesting and challenging topics during my years at his research group. Second, I would like to than my advisor Dr. Anu Lehtovuori for her help and support during this journey. I also wish to thank all the other co-authors: Dr. Jari-Matti Hannula, Mr. Riku Kormilainen, Mr. Albert Salmi, Dr. Pasi Ylä-Oijala, Dr. Janne Ilvonen, and Dr. Alexander Khripkov. Thank you for the fruitful collaboration.

I want to thank the current and former members of group Viikari: Dr. Juha Ala-Laurinaho, Dr. Jari Holopainen, Dr. Joni Kurvinen, Dr. Mikko Leino, Dr. Resti Montoya Moreno, Mr. Jaakko Haarla, Mr. Sabin Karki, Mr. Henri Kähkönen, Mr. Veli-Pekka Kutinlahti, Mr. Quangang Chen, Mr. Matti Kuosmanen, and Mr. Harri Varheenmaa. Thank you for creating a great working environment. I also want to thank Mr. Eino Kahra, Mr. Antti Kuhlberg, and Mr. Matti Vaaja for helping me realize prototypes of my designs.

I want to thank the preliminary examiners of this thesis, Prof. Daniele Cavallo and Prof. Lars Jonsson, as well as Prof. Mohammad Sharawi for agreeing to act as my opponent.

Finally, I would like to thank my family, my parents Päivi and Riku and my sister Sarianna, for all of their support throughout all these years.

Espoo, May 1, 2021,

Rasmus Luomaniemi
Contents

Preface 1

Contents 3

List of Publications 5

Author’s Contribution 7

List of Abbreviations and Symbols 9

1. Introduction 13
   1.1 Objectives of this work ................................ 14
   1.2 Main scientific merits ................................... 15
   1.3 Contents and organization of the thesis .................. 15

2. Antennas in handsets 17
   2.1 Basic properties of handset antennas .................... 17
   2.2 Multiantenna systems .................................. 21
   2.3 Characteristic mode analysis ............................ 23
   2.4 Requirements for modern handset antennas ............... 24
   2.5 Multiport antennas ................................... 28
   2.6 Research methods and tools .............................. 30
      2.6.1 Electromagnetic simulations ......................... 30
      2.6.2 Numerical calculations ............................... 31
      2.6.3 Measurements ....................................... 31

3. Design methods for multiport handset antennas 33
   3.1 Switch-reconfigurable MIMO antenna and design method . 33
   3.2 Unbroken metal rim MIMO antenna based on characteristic
       mode analysis ........................................... 37

4. Adaptive operation and user effect with multiport antennas 43
   4.1 Reducing user effect using multiport techniques .......... 43
## Contents

4.2 Designing hand-immune multiport antennas with characteristic mode analysis ........................................ 48

5. Multiport antennas and bandwidth challenges 57
   5.1 Extremely low-profile antenna for challenging environments in handsets ........................................... 57
   5.2 Multiport Q-factor and bandwidth estimation ............... 65

6. Summary of Publications .................................. 71

7. Conclusions ........................................ 75

References ............................................ 77

Errata .............................................. 91

Publications ......................................... 93
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.


Author’s Contribution

Publication I: “Switch-Reconfigurable Metal Rim MIMO Handset Antenna With Distributed Feeding”

The author had a main responsibility in this work. He developed the design method, designed the proposed antenna, and wrote most of the paper. This work was instructed by Dr. Hannula and Dr. Lehtovuori and supervised by Prof. Viikari.

Publication II: “Unbroken Metal Rim MIMO Antenna Utilizing Antenna Clusters”

The author had a main responsibility in this work. He designed the proposed antenna and wrote most of the paper. Mr. Kormilainen participated in the manufacturing and measurements of the antenna prototype. This work was instructed by Dr. Hannula and Dr. Lehtovuori and supervised by Prof. Viikari.

Publication III: “User effect on antenna cluster based MIMO antenna”

This work is based on the work in Publication II. The author had the main responsibility for performing the measurements, analyzing the results, and preparing the paper. Mr. Kormilainen participated in the measurements and writing of the paper. This work was instructed by Dr. Hannula and Dr. Lehtovuori and supervised by Prof. Viikari.
Publication IV: “Reducing User Effect on Mobile Antenna Systems With Antenna Cluster Technique”

This work is based on the work in Publication I and Publication II. Mr. Salmi performed the measurements with guidance from the author. The author had the main responsibility for analyzing the results and writing the paper. This work was instructed by Dr. Lehtovuori and supervised by Prof. Viikari.

Publication V: “Designing Hand-Immune Handset Antennas with Adaptive Excitation and Characteristic Modes”

This paper is the result of collaborative work. The idea for this work is based on discussions between the author, Dr. Ylä-Oijala, and Dr. Lehtovuori. Dr. Ylä-Oijala provided the simulation codes for the mode analysis and contributed to the simulations and analysis of the results. The author had the main responsibility for designing the final antenna and writing the paper. This work was instructed by Dr. Lehtovuori and supervised by Prof. Viikari.

Publication VI: “Extremely Low-Profile Tunable Multiport Handset Antenna”

The idea for this work is based on collaborative discussions between the author and the co-authors. The author had the main responsibility for developing the antenna design and writing the paper. This work was instructed by Dr. Lehtovuori, Dr. Ilvonen, and Dr. Khripkov and supervised by Prof. Viikari.

Publication VII: “Q-factor for Multiport Antennas and Achievable Bandwidth Estimation”

This paper is the result of collaborative work. The idea for this work is based on discussions between the author, Dr. Ylä-Oijala, and Dr. Lehtovuori. Dr. Ylä-Oijala provided the simulation tool for the field-based quality factor results and participated in developing the impedance-based quality factor formulations with the author. The author had the main responsibility for the presented design process, analysis of the results, and writing of the paper. This work was instructed by Dr. Lehtovuori and supervised by Prof. Viikari.
List of Abbreviations and Symbols

Abbreviations

5G (NR)  fifth generation (New Radio)
ARC    active reflection coefficient
CCE    capacitive coupling element
CM     characteristic mode
CMA    characteristic mode analysis
EFIE   electric field integral equation
EM     electromagnetic
ECC    envelope correlation coefficient
FBW    fractional bandwidth
FDTD   finite difference time domain
FEM    finite element method
FIT    finite integration technique
HB     high band
IC     integrated circuit
ICE    inductive coupling element
LB     low band
LTE    Long-Term Evolution
MFIE   magnetic field integral equation
MHB    middle-high band
MHz    megahertz
MIMO   multiple-input multiple-output
MoM    method of moments
MS     modal significance
PCB    printed circuit board
PEC    perfect electric conductor
List of Abbreviations and Symbols

PIFA  planar inverted-F antenna
PMA  planar monopole antenna
SISO  single-input single-output
SNR  signal-to-noise ratio
TARC  total active reflection coefficient
UWB  ultra-wideband
VNA  vector network analyzer

Operators

()^H  conjugate transpose
()^*  complex conjugate
det  determinant
eig  eigenvalue
max  maximum
min  minimum

Symbols

a  radius of a sphere
\textbf{a}  incident wave vector
\textbf{b}  reflected wave vector
C  capacity
\textbf{C}_T  tunable capacitance
\textbf{D}  radiation matrix
\textbf{F}_i  far-field pattern of the \textit{i}th antenna
\textbf{H}  channel matrix
\textbf{I}_M  identity matrix of size \(M \times M\)
\textbf{J}  surface current density
\textbf{J}_n  electric eigencurrent of mode \(n\)
k  wave number
\textbf{M}_n  magnetic eigencurrent of mode \(n\)
\text{N}_f  number of feeds
\text{N}_{OC}  number of open circuits
\text{N}_T  number of MIMO antennas
P_{acc}  accepted power
P_{av}  available power
List of Abbreviations and Symbols

\( P^{\text{loss}} \)  
loss power

\( P^{\text{rad}} \)  
radiated power

\( P^{\text{react}} \)  
reactive power

\( Q \)  
quality factor

\( R \)  
real part of the impedance matrix

\( R_r \)  
correlation matrix

\( S \)  
scattering matrix

\( S_C \)  
surface of a PEC structure

\( S_D \)  
surface of a dielectric structure

\( W_e \)  
stored electric energy

\( W_m \)  
stored magnetic energy

\( X \)  
imaginary part of the impedance matrix

\( Z \)  
impedance matrix

\( Z_A \)  
antenna input impedance

\( Z_L \)  
load impedance

\( \alpha_n \)  
characteristic angle of mode \( n \)

\( \Gamma \)  
reflection coefficient

\( \eta \)  
efficiency

\( \eta^{\text{match}} \)  
matching efficiency

\( \eta_n \)  
modal efficiency

\( \eta^{\text{rad}} \)  
radiation efficiency

\( \eta^{\text{tot}} \)  
total efficiency

\( \kappa_n \)  
modal coupling parameter

\( \lambda_n \)  
eigenvalue of mode \( n \)

\( \rho \)  
complex correlation coefficient
1. Introduction

Over the past few decades, the internet has greatly changed the way of life for most people. More than half of the global population now have access to the internet, a percentage that continues to increase. In addition to the number of users, there has also been an increase in the number of devices connected to the internet, now actually exceeding the global population. A significant part of the continuously increasing global data traffic is due to wireless and mobile devices. Currently, more than 50% of all internet traffic is due to wireless mobile devices, a percentage that is expected to increase to more than 70% in 2022 [1], [2].

A significant part of the growth observed in the global use of the internet is due to the evolution of mobile phones. Compared to the relatively simple, at least according to today’s standards, voice- and text-based communication devices, modern smartphones have large touchscreens and high-quality cameras and are used to access a large number of online services thanks to fast data connections. With the continuous consumer demand for increasingly higher data rates, wireless communication systems need to be able to meet these new and more demanding goals in the future.

As the part that transmits and receives all radio waves used for wireless communication, antennas play an important role. Increasing the data rates is relatively simple in theory. The capacity of a communication system depends on the used bandwidth. Thus, increasing the frequency bands used increases the data rates. Because the available radio spectrum is inherently limited, using multiple transmitting and receiving antennas simultaneously can increase the spectral efficiency (i.e., how much data can be transferred within a certain bandwidth). Thus, using multiple-input multiple-output (MIMO) techniques can also increase the data rates. However, realizing these goals directly conflicts with the second large trend defining modern smartphones: device appearance and form factor. Recently, the size of the touchscreen has increased to cover almost all of the front part of the device, and visually appealing materials, such as metals and glass, are often used for the rest of the device. As can be seen in Fig. 1.1, the large number of internal components and large battery size leave very little room for the antennas. Increasing the screen-to-body ratio means that this volume also becomes smaller and smaller. According to the very
fundamental properties of antennas, decreasing the size of the antenna while covering a wider frequency band leads to a lower efficiency and, therefore, lower data rates.

With the shift from the current fourth-generation Long-Term Evolution (LTE) technologies to new fifth-generation (5G) systems, one of the main challenges for handset antenna designers is to find a means for realizing all the required antenna systems in a way such that they can be fitted into the extremely challenging environment of current and future handsets. Although most of the attention recently has been drawn to the new millimeter-wave systems operating at frequencies of tens of gigahertz and offering very high data rates, the lower sub-6GHz frequencies will continue to play an important role in the future. For example, the first commercial realizations of 5G operate at 3.5GHz, which is considered a favorable compromise between the data rate and coverage area [3].

A second major problem is the effect of the user in the vicinity of the antenna, which can significantly degrade the antenna’s performance. Typically, handset antennas are designed to operate in free space, although the most common use case is the user holding the device. Traditional antenna solutions have struggled to reach these increasingly difficult goals. Therefore, new ideas and techniques are required to realize antennas for handsets.

## 1.1 Objectives of this work

The objective of this work is to develop new design methods and tools for handset antennas using adaptive multiport antenna techniques. The focus is on finding new ways to utilize the benefits offered by multiple active feeding ports with such antenna structures, which can be integrated into handsets while taking into account the restrictions set by the metal rims and small ground clearances as well as other realistic limitations. New and efficient design tools, required
because of the increasing complexity of multiport antenna systems, are also developed to accelerate the design process of multiport antennas.

1.2 Main scientific merits

The main scientific merits of this thesis are as follows:

1. Developing new design methods and several new antenna designs utilizing multiport techniques on the basis of the combination of theoretical approaches and practical applications for modern handset antennas.

2. Demonstrating different methods for using multiport techniques to improve, for example, the efficiency, bandwidth, and MIMO operation of handset antennas.

3. Showing that multiport antennas can be used to adapt to changing operation conditions, including the user’s hand holding the device and changes in the internal structure of the device, and introducing a method for designing and realizing hand-immune handset antennas.

4. Demonstrating new methods for combining multiport antennas with other techniques, including lumped element matching networks, switches, and tunable components, to realize antenna systems with good performance in the very challenging environment of modern handsets.

1.3 Contents and organization of the thesis

This thesis consists of an overview and seven publications. In Chapter 2, the main properties, parameters, and some essential theories and design tools related to handset antennas are briefly presented for background information. In addition, an overview of state-of-the-art solutions and main challenges is presented. Chapters 3–5 present the actual new scientific work done in this thesis. This overview includes only the most important content from these publications. First, two design methods for multiport handset antennas and the antennas designed using the proposed methods are presented in Chapter 3. Chapter 4 starts by discussing the user effect with multiport antennas with the designs presented in the previous chapter. Then, a new method for designing hand-immune handset antennas is presented. Chapter 5 presents a method utilizing multiport feeding and tunable matching that helps realize extremely low-profile antennas inside smartphones, and then it presents the developed design tool that can be used to accelerate the multiport antenna design process. The publications are summarized in Chapter 6 and the work is concluded in Chapter 7.
2. Antennas in handsets

As antennas are the communication system parts responsible for radiating and receiving electromagnetic (EM) waves, their properties play a significant role in the performance and operation of whole systems [4]. This thesis is focused on antennas for mobile communication applications, more precisely for handsets, utilizing multiple active feeding ports. To allow presenting the multiport theory later on in this chapter and the new results in subsequent chapters, basic properties and concepts are first introduced for more traditional single-feed antennas.

Handset antennas typically have several common properties and limitations which will be introduced first. Moreover, some currently used antenna design tools and methods will be briefly presented. The handset antenna requirements from the viewpoint of both communication systems and industry are also discussed. In addition, antenna designs from the literature are introduced to emphasize the challenges facing modern handset antenna designers and the need for the new solutions developed in this work.

2.1 Basic properties of handset antennas

Since the late 1940s, fundamental limitations for small antennas have been a topic of numerous studies [5]. Small antennas, usually meaning electrically small (i.e., small compared to the wavelength at the operation frequency), can be studied theoretically using spherical modes [6]. One of the most important results from these types of rather theoretical studies relates the minimum quality factor \( Q \), generally defined as \( 2\pi \) times the ratio of the maximum stored energy and the total energy lost by radiation per period, to the electrical size of the antenna as follows [7]:

\[
Q = \frac{1}{(ka)^3} + \frac{1}{ka},
\]

where \( a \) is the radius of a sphere circumscribing the antenna and \( k = 2\pi/\lambda \) is the wave number. The importance of (2.1) stems from the relationship between the Q-factor and the fractional bandwidth (FBW) of the antenna. For single resonance
with a relatively narrow bandwidth, the bandwidth is inversely proportional to
the Q-factor [8]:

\[ \text{FBW} \propto \frac{1}{Q}. \] (2.2)

It should be noted that this proportionality does not generally hold for all
antennas but is presented here to demonstrate the theoretical limitations related
to small antennas [9]. More details about the Q-factor and its relationship with
the bandwidth are presented in Chapter 5.

Equations (2.1) and (2.2) show that if an antenna is made smaller, the Q-factor
increases and, hence, the bandwidth decreases. More generally, the three main
properties that a small antenna should have are shown in Fig. 2.1. Because
of the physical limitations of electrically small antennas, only two of these can
be achieved simultaneously. In practice, this means that if, for example, the
bandwidth is to be improved, either the size has to be increased or the efficiency
will decrease [8]. In addition to these three traditional parameters for the outer
edge of this small antenna "challenge triangle," designers of modern handset
antennas should also take into account the device appearance, robustness, and
manufacturing, among other factors, which are parameters set by the industrial
requirements [10]. These requirements are explained in more detail in Section
2.4.

![Figure 2.1. Challenges of the most important parameters of small antennas.](image)

It should be noted, however, that there is no specific definition for an electrically
small antenna. The most common definitions include \( ka \leq \frac{1}{2} \) and \( a \leq \frac{1}{2\pi} \) [11],
[12]. The sizes of modern smartphones, about 150 × 75 mm², imply that these
conditions are actually not necessarily met, and the antennas cannot be, strictly
speaking, defined as electrically small. However, the main challenges in handset
antennas, especially at lower frequencies below 1GHz, follow these limitations
very closely. In other words, the most important challenge is usually to achieve
the required bandwidth with a high efficiency while keeping the size of the
antenna as small as possible.

The bandwidth of an antenna can be defined on the basis of different antenna
properties depending on the application. Some definitions include radiation
pattern, beamwidth, polarization, gain, impedance, reflection coefficient, and
efficiency [13]. In this work, bandwidth refers to the reflection coefficient and
efficiency. The voltage reflection coefficient for a single antenna can be calculated
as [14]

\[ \Gamma = \frac{Z_A - Z_L^*}{Z_A + Z_L}, \] (2.3)

where \( Z_A \) is the input impedance of the antenna and \( Z_L \) is the impedance of the
load connected to the antenna, in practice, the integrated circuit (IC) transceiver, and \(Z^*\) is the complex conjugate. In this work, the load impedance is assumed to be 50\(\Omega\). When the antenna impedance and load impedance do not satisfy the condition \(Z_A = Z_L^*\), known as conjugate matching, the antenna is said to be mismatched, meaning that part of the power fed to the antenna is reflected back.

This previous definition for matching, as in (2.3), holds when there exists only one antenna. In most practical applications in modern handsets, there are several different antennas with their own feeding ports. These can be used, for example, for different antennas with different frequency bands, for multiple antennas simultaneously in the same frequency band (for more details, see Section 2.2), or for combining the operation of multiple feeding ports to improve certain properties of an antenna (for more details, see Section 2.5). Regardless of the use, the common factor between all of these cases is the interaction between these antennas, which affects the operation of each individual antenna.

Scattering parameters, or S-parameters, are often used to characterize the operation of systems with multiple feeding ports. These S-parameters are defined as [15]

\[
S_{ij} = \frac{b_i}{a_j} \bigg|_{a_k = 0 \text{ for } k \neq j}, \quad (2.4)
\]

where \(a\) and \(b\) represent the incident and reflected power waves defined as in [16]. An antenna system with \(N\) ports is, hence, described as

\[
\begin{bmatrix}
    b_1 \\
    b_2 \\
    \vdots \\
    b_N
\end{bmatrix} =
\begin{bmatrix}
    S_{11} & S_{12} & \cdots & S_{1N} \\
    S_{21} & S_{22} & \cdots & S_{2N} \\
    \vdots & \vdots & \ddots & \vdots \\
    S_{N1} & S_{N2} & \cdots & S_{NN}
\end{bmatrix}
\begin{bmatrix}
    a_1 \\
    a_2 \\
    \vdots \\
    a_N
\end{bmatrix}, \quad (2.5)
\]

or written in a more compact form as

\[
b = Sa. \quad (2.6)
\]

When every port is terminated with the reference impedance, \(S_{ii}\) provides the reflection coefficient of port \(i\). Here, the \(S_{ij}\) terms are the coupling coefficients that describe how much of the power fed to port \(j\) is coupled to port \(i\).

In addition to the reflection coefficients, the performance of an antenna is often described with efficiency. Using the reflection coefficient, the matching efficiency for a single-port antenna can be defined as

\[
\eta_{\text{match}} = 1 - |\Gamma|^2 = \frac{P_{\text{acc}}}{P_{\text{av}}}, \quad (2.7)
\]

which describes how much of the available power (\(P_{\text{av}}\)) is accepted (\(P_{\text{acc}}\)) by the antenna [14]. For systems with multiple ports, the matching efficiency of port \(i\) can be defined as [17]

\[
\eta_{\text{match}_i} = 1 - |S_{ii}|^2 - \sum_{i \neq j}^N |S_{ij}|^2, \quad (2.8)
\]
to take into account the power coupled to other ports in addition to the reflected power.

It should be noted that the materials from which the antenna is made as well as the materials in the near vicinity of the antenna affect its efficiency, that is, how much of the power accepted by the antenna is actually radiated. Because of resistive and dielectric losses, part of the accepted power is converted into heat in lossy materials, such as the user’s hand. The ratio of the radiated power ($P_{\text{rad}}$) to the accepted power is known as the radiation efficiency:

$$\eta_{\text{rad}} = \frac{P_{\text{rad}}}{P_{\text{acc}}}.$$  \hfill (2.9)

Combining the matching efficiency and radiation efficiency gives the ratio of the radiated power to the available power, known as the total efficiency:

$$\eta_{\text{tot}} = \eta_{\text{match}}\eta_{\text{rad}} = \frac{P_{\text{rad}}}{P_{\text{av}}}.$$  \hfill (2.10)

The total efficiency is one of the most important parameters for handset antennas. In older publications, only matching has often been considered in the evaluation of antenna performance, possibly because it can be measured relatively easily with a vector network analyzer (VNA). Traditionally, a $-6\,\text{dB}$ reflection coefficient has been considered as sufficient for handset antennas. However, matching does not necessarily describe the true performance well because it does not consider coupling to other ports or losses. Therefore, good matching does not always correspond to a good total efficiency. Generally, total efficiency is a better parameter for describing the performance of antennas. There does not exist any generally accepted minimum level for total efficiency of different antennas. At some point, 40% was often referred to as good efficiency level for handset antennas. However, with decreasing volume available for the antennas, increasing number of antenna systems, and wider frequency bands, it is not always reached anymore, especially in the most challenging sub-1GHz frequencies. From the perspective of the whole communication system, also other parts have significantly developed, meaning that acceptable data transfer performance can be achieved even with lower antenna efficiencies. This can be seen, for example, in radiation properties of commercial devices where radiation efficiencies below 20% have been observed at frequencies below 2.5GHz [18]. Instead of reaching a certain predefined total efficiency level, the task of modern antenna designers can rather be seen as maximizing the performance in the given environment and limitations.

The different types of antennas used in handsets can be divided roughly into two categories on the basis of the behavior of their impedance: self-resonant antennas and non-resonant antennas. Self-resonant antennas have impedance that can be matched to the load impedance without any additional circuitry by tuning the physical shape and dimensions of the radiating parts of the antenna. Non-resonant antennas are tuned to resonate with external matching networks consisting usually of lumped inductors and capacitors, especially in the sub-6GHz frequencies.
Before the emergence of smartphones with large touchscreen in the late 2000s and early 2010s, self-resonant antennas have been the most commonly used antenna type in handsets. Most antenna designs back then were based on planar inverted-F antennas (PIFAs) or planar monopole antennas (PMAs). These types of antennas allowed good impedance matching on two (or more) bands with proper shaping of the antenna structure and placement of the feeding port and ground connections. More design parameters can be achieved using, for example, dielectric loading or parasitic elements [19]–[22]. A useful overview as well as more details on these types of antennas used in real commercial products can be found in [23].

In particular, at low frequencies below 1GHz, the main source of radiation is actually the metallic chassis of the device instead of the antenna element [24]. By utilizing these ground-plane modes, which are excited with the so-called coupling elements [25], the size and complexity of the antenna element can be reduced relative to that of self-resonant antennas, such as PIFAs. The two main types of coupling elements are capacitive coupling elements (CCEs) [24], [25] and inductive coupling elements (ICEs) [26]. As coupling elements are inherently non-resonant antennas, they require a matching network to radiate well on the required frequency bands. This means that at least part of the complexity of the design task is moved to the design and optimization of the matching networks [27]–[29].

Although the antennas mentioned here were classified into self-resonant antennas and non-resonant coupling-element-based antennas with matching circuits, such classification is not that simple especially with more modern antenna designs. Antenna designs often exhibit properties from both of these classes. For example, the bandwidth of PIFAs can be extended with external matching components. Coupling-element-type antennas also require heavy optimization of the shape, size, and location of the element in addition to matching network optimization.

### 2.2 Multiantenna systems

Recently, with the increasing demand for higher data rates, multiantenna systems have become one of the most important techniques for improving the spectral efficiency of mobile communication systems. Multiple antennas at the transmitter and receiver can be used in different manners, depending on the use scenario and requirements. The two main multiantenna techniques are diversity systems [30] and MIMO systems [31]. In diversity systems, the goal is to improve the link reliability by receiving the same transmitted signal with multiple receiving antennas through independent propagation channels. This allows combining the received powers from the antennas in a useful way to reduce the degradation of the signal-to-noise ratio (SNR) due to the small-scale fading of the propagation environment compared to single-antenna systems.
MIMO systems utilize spatial multiplexing (i.e., the multipath propagation environment) to transmit and receive several different data signals, which allows for a significant improvement in the channel capacity compared to that achieved with single antenna systems [32]. MIMO communication requires a rather complex system that includes the effects of the antennas, wave propagation, and signal processing [31]. In this work, the focus is on antennas for handsets, particularly the MIMO performance of these antennas.

The most important parameters of handset antennas, regardless of whether they are used to improve the link reliability or the capacity, are the total efficiency of the individual antennas and the correlation between the antennas (i.e., how similar their radiation patterns are). The complex correlation coefficient between two antennas is calculated from the far-field patterns $\mathbf{F}$ as follows [33]:

$$
\rho_{ij} = \frac{\iint_{4\pi} \mathbf{F}_i \cdot \mathbf{F}_j^* \, d\Omega}{\sqrt{\iint_{4\pi} \mathbf{F}_i \cdot \mathbf{F}_i^* \, d\Omega \iint_{4\pi} \mathbf{F}_j \cdot \mathbf{F}_j^* \, d\Omega}}.
$$

(2.11)

To present and compare the correlations of different antennas, the envelope correlation coefficient (ECC) [34] is often used:

$$
\text{ECC}_{ij} = \left|\rho_{ij}\right|^2.
$$

(2.12)

Typically, ECC values below 0.5 are considered sufficiently low, meaning that the degradation of the capacity due to correlation is small.

The capacity per 1 Hz of bandwidth for a system with $M$ transmitting and receiving antennas can be calculated as follows [35]:

$$
C = \log_2 \left( \det \left( \mathbf{I}_M + \frac{\text{SNR}}{M} \mathbf{H} \mathbf{H}^H \right) \right),
$$

(2.13)

where $\mathbf{I}_M$ is an identity matrix of size $M \times M$. In this equation, $\mathbf{H}$ is the MIMO channel matrix, which is calculated as

$$
\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_W
$$

(2.14)

when only the effects of the receiving antennas of the mobile device are taken into account and ideal antennas are assumed for the transmitting base station. $\mathbf{H}_W$ represents a Rayleigh fading propagation channel (i.e., one with a rich scattering environment), modeled with a matrix of independently and identically distributed complex Gaussian random variable entries. The correlation matrix $\mathbf{R}_r$ describes the effect of the antennas, including the efficiency and complex correlation coefficients.

It should be noted that the capacity calculated from (2.13) is valid only for one channel realization. To obtain a more suitable parameter, the average value from a large number of different channel realizations, ergodic capacity, is used [36]. In this study, the MIMO capacity is used to obtain a single parameter that describes performance as part of the whole MIMO system. In addition, the maximum capacity that a system with 100% efficient antennas with zero correlation would have can be used as a reference to which the achieved capacities can be compared.
2.3 Characteristic mode analysis

While the challenges facing handset antenna designers have significantly increased from the first generations of mobile communication systems to modern devices with multiple wide frequency bands and several MIMO antennas, new design tools have also been taken into use. One of the most important tools is characteristic mode analysis (CMA) [37]. The original theory behind this tool was actually presented in the 1970s [38]–[40]. Characteristic modes (CMs) are the natural orthogonal resonance modes of a structure without any excitations applied, and they depend only on the size and shape of the structure.

The basis of solving these modes numerically is the generalized eigenvalue equation formulated for a perfect electric conductor (PEC) structure:

$$ X(J_n) = \lambda_n R(J_n), \quad (2.15) $$

where $R$ and $X$ are the real and imaginary parts, respectively, of the impedance matrix solved from the electric field integral equation (EFIE) or magnetic field integral equation (MFIE) discretized with the method of moments (MoM) [41]. Here, $\lambda_n$ and $J_n$ are the eigenvalues and eigenvectors, or eigencurrents, of mode $n$, respectively. The eigenvalues can be used to calculate several parameters describing the properties of each mode. The most common ones are the modal significance,

$$ MS = \frac{1}{1 + j \lambda_n}, \quad (2.16) $$

and the characteristic angle,

$$ \alpha_n = 180^\circ - \tan^{-1}(\lambda_n). \quad (2.17) $$

The modal significance is a number in the range $[0,1]$, where the value 1 means that the CM is in resonance. This describes how well a mode can radiate at different frequencies and how well it can couple to external excitations. A CM is usually considered significant in the frequency range where $MS \geq \frac{1}{\sqrt{2}}$, and this also predicts the bandwidth potential of the mode [37]. The characteristic angle includes similar information on the CM’s ability to radiate efficiently as well as on the bandwidth. The mode is considered to be in resonance at $\alpha_n = 180^\circ$, and values of $\alpha_n = 90^\circ$ and $\alpha_n = 270^\circ$ correspond to modes storing energy. The slope of the characteristic angle curve near the resonance predicts the bandwidth potential of the CM [42].

After the characteristic mode theory was first developed, some applications, including antenna shape synthesis and antenna pattern synthesis, were published [43], [44]. However, the number of published works on the topic remained low for a long time. CMA started gaining interest again within the antenna design community when its potential and benefits for mobile antenna designs were discovered after the role of the chassis radiation modes and coupling element antennas was understood. It should also be noted that the recent increase in the computational power has made it a practical tool.
CMA offers several benefits for handset antenna designers thanks to the physical insights of the natural resonance modes of the studied structures. In addition to modal significance and characteristic angle, the surface current distributions of modes are considered to be extremely useful when designing the placement of exciter elements. A certain mode can be excited with CCEs located near the current minima or with ICEs placed near the current maxima [45], [46]. CMA can, therefore, be used to explain the results for the optimal placement of coupling elements for handset ground-plane radiation modes found already before the CMA was used [47], [48]. Because of the orthogonality of the modes, CMA can also be used to design MIMO antennas. As the ground-plane mode is the main radiator at frequencies below 1GHz, the largest benefits are usually obtained at these frequencies [49]–[53], although recently some designs in which CMA has been applied also at higher frequencies have been published [54]. Another important application for CMA in handset antennas is the merging of modes for improved bandwidth. By analyzing the properties of the CMs, structure modifications and exciting schemes can be designed so that multiple modes can be excited simultaneously to increase the bandwidth [55], [56]. Other recent examples of utilizing CMA in handset antenna design have been published in [57]–[60].

In addition to handset antennas, CMA can be utilized in a wide range of antenna design problems [61]. Some examples include the design of ultra-wideband (UWB) PMAs [62], [63], antennas for laptop computers [64], base station antennas [65], [66], slot antennas [67], antennas for smartwatches and other wrist-worn devices [68], [69], antennas with defected ground-plane structures [70], and antennas with stable radiation pattern characteristics [71]. In the recent years, new application areas for CMA have been found, for example, in the design of low-profile patch antennas and metasurface antennas [72]–[75], plasmonic nanoantennas [76], [77], and antenna arrays [78]–[80]. In addition, the theory and computational tools are still developed further [81]–[83] and new concepts and design tools based on CMA have also been published [84], [85].

However, the previous theory and presented results include only PEC structures. Therefore, recently, the CMA theory has been extended to include lossy dielectrics [86], [87], allowing the analysis of the antenna structure modes with the modes of a lossy object (e.g., the user’s hand holding the device) [88], [89]. In this thesis, CMA is utilized in [II] for PEC structures and in [V] for lossy structures.

### 2.4 Requirements for modern handset antennas

If it were up to antenna designers, smartphones would have probably looked really different from what the commercial products actually look nowadays. As discussed in Section 2.1 and seen in Fig. 2.1, not all the desired parameters can be achieved simultaneously, hence requiring compromises. The requirements for
modern smartphone antennas are mainly driven by two conflicting goals. First, increasing the data transfer rates requires new and wider frequency bands to be covered and multiple antenna systems to be fitted into the devices for MIMO operation. Second, the volume of the antennas should be as small as possible, and their physical structure and visual appearance should be suitable from an aesthetical point of view.

Starting from the latter, the most visible change in smartphones over the last decade has been the increase of the whole device size, especially the size of the screen. Fig. 2.2 shows the development of the area of the display and clearance area (i.e., the area on the front panel that is not part of the display) for a commercial smartphone model. Given that the size of the screen has increased by 88%, the clearance area has decreased by more than 50%. Increasing the display size and decreasing the clearance area mean that the volume in which the antennas are typically placed has also decreased.

As modern smartphones offer a wide range of features in a relatively small device, the components inside the device are very tightly packed, with very little space available for the antenna. Fig. 2.3 shows an illustrative view of the main components of a modern smartphone. The battery takes up most of the inner volume, whereas the rest of the volume is taken up by the main logic board, including the digital circuitry, memory modules, radio systems, and other required components [91]. A large touchscreen can also have an effect on the operation of the antenna since it consists of a glass panel on the outer edge and a metallic microwave shield on the inner side (with several component layers in between), which is very close to the metal rim where the antennas are typically placed [92]. While using a very realistic simulation model is naturally possible [93], [94], it might be overly complicated for the purpose of academic research. However, it is important to also keep the real requirements in mind within the academic community. Many publications nowadays do include a study on more simplified smartphone models. Typically, these include at least a model for the battery and the screen. In most of the cases, the addition of the screen and battery does not significantly change the operation of the antennas.
However, if the device model is inadequate from the beginning (e.g., with a solid ground plane smaller than the real size of the screen), then the addition of component models can have a significant effect [95].

Another important factor that affects the antennas is the materials from which the device is made. Unlike fully plastic-covered devices in the past, most modern devices utilize much more metallic parts for visual appeal as well as mechanical robustness. A few years back, many top-of-the-line smartphones had a full metal cover, meaning that the device had both a metal rim and a metallic back cover. This metallic back cover may contain slots, which can be utilized for the antennas [96], [97], or it may be fully metallic, making the realization of antennas even more challenging [98], [99]. Currently, the most common choice is to use a glass or plastic back cover (to enable, e.g., wireless charging) and a metal rim. Since adding a metal rim to the device, as well as other internal components, can have a large influence on the operation of the antennas [100], utilizing designs with only a printed circuit board (PCB), without any metal rim or other components [101], [102], for practical use in current metal-rimmed smartphones is most likely impractical.

To enable increased data traffic, mobile communication frequency bands have been extended in the latest generations. The sub-6GHz frequencies have been divided into a large number of bands for LTE and 5G New Radio (NR) systems [103], [104]. Table 2.1 lists all the frequency ranges that have been focused on in this work. The three continuous bands are the 700–960MHz low band (LB), the 1700–2700MHz middle-high band (MHB), and the 3300–4200MHz high band (HB).

As mentioned, a metal rim is a popular option for high-end smartphones because of its visual and mechanical properties. The ultimate goal is to have an unbroken metal rim around the device. In recent years, several antenna designs for these types of devices have been published [52], [105]–[110]. A common option is to form several loop structures to the rim and the PCB ground plane with grounding pads and to excite the loop modes with a capacitive feeding line or by directly feeding the rim [105]–[109]. Another option is to utilize...
Table 2.1. Frequency ranges and their abbreviations used in this work, as well as examples of LTE and 5G NR bands at these frequencies

<table>
<thead>
<tr>
<th>Name</th>
<th>Frequency range (MHz)</th>
<th>LTE bands</th>
<th>5G NR bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB</td>
<td>700–960</td>
<td>5, 8, 12, 13, 17, 18, 20, 26, 28</td>
<td>n5, n8, n12, n20, n28</td>
</tr>
<tr>
<td>MHB</td>
<td>1700–2700</td>
<td>1, 2, 3, 4, 7, 25, 30, 34, 38, 39, 40, 41, 66</td>
<td>n1, n2, n3, n7, n25, n38, n40, n41, n66</td>
</tr>
<tr>
<td>HB</td>
<td>3300–4200</td>
<td>42, 46</td>
<td>n77, n78</td>
</tr>
</tbody>
</table>

the resonance modes of the rim [52], [110]. One of the main challenges with continuous rims is the increased coupling between the antennas, which makes it difficult to realize multiple antennas for MIMO operation. Moreover, achieving a wide bandwidth is often challenging, for example, for the 700MHz band or for extending the operation to the 3.5GHz HB.

Because of such challenges with unbroken metal rim antennas, a popular option is to cut some slots in the rim. Different options for utilizing these sections of the rim have been studied. One of the most popular options is to have one or more sections of the rim at the short end of the device, which is used as the actively fed antenna element, combined with grounding strips or reactive grounding [111]–[115]. Similar to unbroken rims, slotted rims can also be used to excite radiating currents in the rim sections and internal structures of the device [57], [116]–[119]. Different types of slots utilizing rims and ground planes have been proposed [120], [121].

With the introduction of the 5G and new frequency bands around 3.5GHz, many antenna designs for 4-, 8-, 10-, or even larger-order MIMO systems have been recently published. These designs usually utilize similar antenna elements divided around the ground plane [54], [122]–[131] or tightly packed antenna pairs with mode orthogonality, or other means of decoupling, to allow more efficient use of antenna volume [132]–[144]. Several designs for devices with slotted metal rims have been proposed [145]–[149].

One option to improve the operation of handset antennas is to implement frequency tunability or reconfigurability. Making the antenna operate on narrower instantaneous bands allows generally improving the performance [150]. Such tunability is most often realized by including tunable elements in the matching circuits or as aperture matching components. Common options include varactor diodes [151]–[154], on/off-type switches [155], [156] or switches between different reactive loads [157], [158], microelectromechanical systems (MEMS) tunable components [159], [160], and other tunable capacitors [60], [161], [162].

Although the presented designs fulfill some of the desired criteria, required frequency bands, number of MIMO antennas, physical size, and integrability
with the metal rim, most of them have weaknesses. In many of the LTE designs, the full LB from 700 MHz is not covered [52], [57], [107]–[109], [112]–[116], [119], [120], MIMO is not included [57], [105]–[108], [110]–[113], [116], [118], [119], or the clearances are too large for modern handsets [105], [106], [108]–[111], [116], [117], [119]–[121]. For 5G MIMO designs, the problems are usually related to not covering a wide enough frequency band [54], [124], [128], [132], [133], [135]–[137], [139]–[142] or integrating the antennas in a device form factor together with antennas for other bands and MIMO. Most of the proposed designs do not include a metal rim at all, or they require large numbers of slots in the rim. It is also typical to study and design only these HB antennas, and the volume reserved for the LB and MHB antennas is often left impractically small [122], [124], [128]. Therefore, it can be concluded that there still exist many challenges related to sub-6GHz handset antennas and that new solutions are required to reach such very challenging goals.

2.5 Multiport antennas

To improve the performance of handset antennas, new techniques are required. One option that has been gaining increasing interest recently is to utilize multiple feeding ports. One such multiport antenna method is the antenna cluster technique originally proposed in [163], [164]. This technique is based on the collaborative use of several coupled actively fed ports. Combined with weighted feeding signal amplitudes and phases, coupling can be beneficially utilized to improve the antenna’s performance. This technique is utilized and developed further throughout this work in [I]–[VII].

The basis of the cluster technique is to use several antenna elements simultaneously as one antenna. The signals fed to the ports are also coupled to the other ports. The active reflection coefficient (ARC) of port $i$ is also affected by the coupling parameters and incident power waves of the other ports [165]:

$$\text{ARC}_i = \frac{b_i}{a_i} = \sum_{j=1}^{N} S_{ij} \frac{a_j}{a_i}. \quad (2.18)$$

When the coupled signals and signals reflected from the ports have proper weighting, parts of the reflections cancel out and the radiated power is increased. To describe the operation of multiple ports used collaboratively, the total active reflection coefficient (TARC), corresponding to the traditional reflection coefficient of single-port antennas, is often used:

$$\text{TARC} = \sqrt{\frac{\sum_{i=1}^{N} |b_i|^2}{\sum_{i=1}^{N} |a_i|^2}} = \frac{\sqrt{b^H b}}{\sqrt{a^H a}}. \quad (2.19)$$

The efficiency of an antenna cluster with feeding signals $a$ is [163]

$$\eta = \frac{a^H Da}{a^H a}, \quad (2.20)$$
where \( \mathbf{D} \) is the so-called radiation matrix and \( \mathbf{S}^H \) is the conjugate transpose. The radiation matrix can be calculated from the S-parameters under an assumption of a lossless antenna as follows:

\[
\mathbf{D} = \mathbf{I} - \mathbf{S}^H \mathbf{S}.
\]  

(2.21)

In case the system includes more than one cluster, \( \mathbf{S} \) represents a scattering matrix including only the columns corresponding to the elements of the active cluster in order to properly take into account the power coupling to the feeds of the other clusters [166]. If (2.21) is used, the resulting efficiency, as seen in (2.20), will correspond to the matching efficiency. That is, it does not take losses into account and is, therefore, suitable for lossless or low-loss antennas operating in free space. If the antenna structure has losses, or if the antenna is used in a lossy environment, the radiation matrix can be calculated from the far-field radiation patterns [33], [166]:

\[
D_{ij} = \frac{1}{4\pi} \int_\Omega F_i \cdot F_j^* d\Omega,
\]  

(2.22)

where \( F_i \) is the far-field pattern of the \( i \)th element. In this case, the resulting efficiency corresponds to the total efficiency.

A key factor in the operation of an antenna cluster is to properly determine the complex feeding weights. Because (2.20) is in Rayleigh quotient form, the complex feeding weights maximizing this efficiency can be found as the eigenvector corresponding to the largest eigenvalue of the radiation matrix [167]:

\[
\eta_{\text{max}} = \max\{\text{eig}(\mathbf{D})\}.
\]  

(2.23)

Because the optimal feeding weights depend on the frequency, the cluster can be tuned to operate at the maximum efficiency at each frequency by changing the weights accordingly.

With multiport antennas, there are more degrees of freedom that affect the total efficiency than with traditional antennas. Fig. 2.4 illustrates these different factors. The frequency-dependent feeding signals, the matching networks, the reflection coefficients of the ports and coupling between them, and the radiation properties of the elements all determine the total efficiency. For example, coupling is an important factor in multiport antennas [168]. This means not only that these can be utilized to improve the performance in comparison to traditional solutions, but also that the design and optimization process is often more complicated because all of these factors need to be considered simultaneously.

For a practical realization, there is a need for a method to apply these frequency-dependent weights. This can be done, for example, with a multi-channel transceiver IC. The effects of the properties of this transceiver circuit have been studied in [169], and a realization of such a circuit along with the measurement results of a combination of an IC and an antenna cluster is presented in [170]. In this work, however, we focus on the antenna part of the system.
In addition to the single-input single-output (SISO) and MIMO designs in [164], [166], the cluster technique for handset antennas has also been utilized in [171], [172], in which the multiport technique has been combined with a combinatory feeding method (i.e., changing the number of active feeds depending on which combination leads to the highest performance). Other antenna designs based on multifeed structures include injection matched patch antennas [173]–[176], different types of designs based on two-port differential feeding [177]–[181] and other designs based on fixed power divider networks [182].

2.6 Research methods and tools

Modern antenna designs are based on two main tools: numerical computer simulations and measurements of physical prototypes. This section briefly introduces the main tools that have been used in this work.

2.6.1 Electromagnetic simulations

The design process of modern handset antennas relies on numerical EM simulations, because the antenna properties cannot be solved with analytical means in practice. Numerical EM simulations are based on discretizing the studied 3D structure with the simulation mesh and then numerically approximating the solution to Maxwell’s equations for this grid. The most common methods used for antenna simulations are the MoM and finite element method (FEM) for frequency domain simulations and the finite difference time domain (FDTD) and finite integration technique (FIT) for time domain simulations [183]. One of the main differences between these methods is the type of discretization used. Both FDTD and FIT use a hexahedral mesh, whereas MoM and FEM usually utilize a tetrahedral mesh, which can model complex geometries with a high accuracy, better than the hexahedral mesh.

Most of the simulations presented in this thesis have been performed with the commercial simulation package CST Studio Suite [166]. Both FIT and
FEM solvers are used in different cases and are also used to verify that both provide similar results. Due to the formulation of the CMA theory, MoM is used for all modal analysis simulations. The CMA simulations in [II] have been performed with CST, whereas those in [V] have been performed with an in-house code developed at the Department of Electronics and Nanoengineering, Aalto University.

2.6.2 Numerical calculations

In addition to EM simulations, other numerical calculations have also been used. In this work, these mainly include matching network design and optimization and processing of antenna cluster data. These tools were developed by the author. In this work, MATLAB was used for numerical calculations [184].

2.6.3 Measurements

Although the advanced simulation tools and computational power of modern computers have made it possible to achieve a high accuracy with simulations, it is important to also verify the operation with measurements of real prototypes. Two main types of antenna measurements have been used in this work. Port parameters (i.e., S-parameters) were measured with a VNA. Although VNA measurements are quick to perform and can provide a quick look on whether the antenna resonates on the designed frequencies or not, the real performance can only be found by measuring the radiation properties of the antenna. All the radiation properties (i.e., far-field radiation patterns and total efficiency) have been measured with the MVG StarLab [185] antenna measurement system at Aalto Electronics-ICT.

To measure the performance of the multiport antennas studied in this thesis, measurements are performed in the following manner. First, the radiation patterns of each feeding port are measured individually, while the other ports are terminated with 50Ω loads. Then, the feeding weights are calculated using these patterns, and the radiation patterns of each multiport antenna cluster are calculated by numerically combining the element patterns with the feeding weights applied. Finally, these combined patterns are used to calculate the total efficiency, ECC, MIMO capacity, and other required parameters.
3. Design methods for multiport handset antennas

This chapter describes two design methods for multiport handset antennas presented in [I] and [II]. Section 3.1 introduces a new design method based on a multiport simulation model and an evaluation algorithm, which allows efficiently evaluating large numbers of different antenna structures, along with an antenna designed with this method. Section 3.2 introduces a multiport antenna design for handsets with an unbroken metal rim designed using CMA.

3.1 Switch-reconfigurable MIMO antenna and design method

Designing modern handset antennas often requires the designer to solve a complicated optimization problem. If the size, shape, location, and other details of sometimes very complex structures with multiple antenna elements are optimized, a large number of time-consuming EM simulations are required. This means that designing handset antennas with demanding performance goals can lead to a process that requires a very long time. In addition, finding radically new and different ideas to reach these challenging goals is often very difficult with traditional design methods. Therefore, new and efficient design methods are required.

A new design method based on a single multiport EM simulation and an evaluation algorithm using circuit simulations has been developed in [I]. By transforming the problem from a computationally demanding EM problem to a very computationally efficient circuit problem, the design process can be significantly accelerated. Moreover, by studying a very large number of different antenna structures systematically with an evaluation algorithm, the designer does not have to make any assumptions about the structure beforehand, hence making it possible to find new and surprising solutions that would otherwise be very difficult to discover.

The basic idea of the method is shown in Fig. 3.1. An antenna model with several unit antenna elements (i.e., similar elements which are replicated to form the whole antenna structure) with a feeding port and a port connecting or disconnecting the unit elements is first simulated. Then, the optimal way for
Design methods for multiport handset antennas

placing the feeding ports and the open or short circuits is found. In Fig. 3.1a, four unit elements are used and two feeding ports and two open circuits are placed in the possible feeding ports, as shown in the circuit representation in Fig. 3.1b.

For a practical application example, this method was applied for a handset antenna design for a metal-rimmed device in [I]. To utilize the metal rim as efficiently as possible, the multiport cluster technique and switches are utilized. In practice, switches allow the use of different structures for LB and higher frequencies so that larger elements can be used at the challenging low frequencies while a larger number of MIMO antennas can be used for higher frequencies. The EM simulation model is shown in Fig. 3.2. To limit the number of possible options for the evaluation algorithm, only half of the perimeter is covered with the unit antenna elements. After this model is used to find the most potential candidates, the structure is mirrored to form the full structure.

Fig. 3.3 shows a more detailed operation principle of the evaluation algorithm. In Fig. 3.3a, the general process is described. Because it is usually more challenging to achieve good performance with LB frequencies, optimization is first performed for the LB structure. The MHB and HB frequencies are then

Figure 3.1. Basic principle of the design method with (a) a multiport simulation model and (b) a circuit representation of finding the optimal combination of feeding ports and open or short circuits. [I]
Design methods for multiport handset antennas

Figure 3.3. (a) Design process steps and (b) more detailed flowchart of the evaluation algorithm.

optimized on the basis of the LB results. This allows the designer to utilize the same feed locations and open/short circuits so that the number of switches required for the final structure can be kept as small as possible. A more detailed description of the algorithm is presented in Fig. 3.3b. All possible combinations for the chosen number of data streams, i.e., MIMO order $N_T$, the number of feeds in an antenna cluster $N_f$, and the number of open circuits in the rim $N_{OC}$, are first created. Using the S-parameters, as in (2.21), the matching efficiency, as in (2.20), is calculated for all the possible combinations, and the most promising ones are chosen for the full structure study. To include other parameters affecting the performance besides efficiency (e.g., correlation), a full structure evaluation is performed for the total efficiency and MIMO capacity $C$. Finally, when the unit elements are combined into the final elements and the unused feedlines are removed, the operation can slightly change. To take this into account and make sure that the best performance is achieved, a final optimization step is performed to fine-tune the locations of the feeds, metal rim slots, and switches.

The optimization method developed was used to design a MIMO handset

Figure 3.4. (a) Simulation model and (b) measured prototype of the proposed antenna design. [I]
antenna system. After studying different parameters for the described design method, two-element MIMO for the 0.7–0.96GHz LB and four-element MIMO for the 1.7–2.7GHz MHB and 3.0–4.0GHz HB were chosen with two feeds in each antenna cluster. Switches were realized with PIN diodes, with a total of 10 of these switches. The simulation model of the final antenna structure is shown in Fig. 3.4a, along with a photograph of the measured prototype in Fig. 3.4b. Table 3.1 presents the antenna cluster port configurations.

Table 3.1. Antenna cluster port configurations [I]

<table>
<thead>
<tr>
<th></th>
<th>Data stream</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB</td>
<td>Ports</td>
<td>p1, p4</td>
<td>p5, p8</td>
</tr>
<tr>
<td>HB</td>
<td>Ports</td>
<td>p1, p2</td>
<td>p3, p4</td>
</tr>
</tbody>
</table>

Fig. 3.5 shows the simulated and measured total efficiencies, and Fig. 3.6 shows the MIMO capacity. The efficiency achieved is 30–40% in the LB, 50–70% in the MHB, and 25–75% in the HB. The correlation results demonstrate good ECC performance with values below the usual threshold of 0.5 in the whole frequency band. The MIMO capacity is about 8bits/s/Hz in the LB, 19–20bits/s/Hz in the MHB, and 17–19bits/s/Hz in the HB. These correspond to about 71% of the ideal 2×2 capacity in the LB and 77–90% of the ideal 4×4 capacity in the MHB and HB. More details on the design process and the results can be found in [I].

Given the relatively small 5mm clearance at the short edge of the device and the height of only 4mm, the achieved results can be considered very good. Even in relatively new designs, ground clearances of 7mm up to more than 10mm are still used, although these are impractically large for any real handsets. With
Design methods for multiport handset antennas

Figure 3.6. MIMO capacity performance of the designed antenna. [I]

other published designs, MIMO operation is often limited to a maximum of two in the LB and MHB. In many designs, the HB operation is not considered at all and the LB operation does not always cover the whole band starting from 700MHz. Keeping these factors in mind, the developed optimization method can be used to design antennas with properties that are not found in many publications.

3.2 Unbroken metal rim MIMO antenna based on characteristic mode analysis

As discussed in Section 2.4, having an unbroken metal rim in a smartphone is a highly desired feature thanks to its visual and mechanical properties. For antenna designers, however, this causes different challenges. The presence of such a continuous metal rim causes different antenna elements to suffer from high coupling, making it particularly challenging to design MIMO antennas. Thanks to the antenna cluster technique, this coupling is not always a negative feature. Because there needs to be enough coupling for the elements to efficiently operate as a cluster [168], this coupling due to the rim can actually be used in a useful way. In [II], an antenna design for a device with an unbroken metal rim utilizing multiport antennas was presented. Different ways to utilize the benefits that the cluster technique offers, depending on, for example, the frequency response and type of coupling between the elements, are demonstrated with this design.

To be able to design the elements for the clusters with the right amount of coupling, in addition to low coupling and correlation for elements in different clusters, CMA, as discussed in Section 2.3, can be used, especially in the sub-1GHz frequencies. Fig. 3.7 shows the modal analysis results for a ground plane with an unbroken metal rim. At the LB frequencies, there are two orthogonal modes with a similar resonance frequency, as can be seen from the eigenvalues in Fig. 3.7a. The results also suggest that the first of these modes has a larger bandwidth potential. Therefore, the goal in [II] was to utilize mode 1 to cover the
Design methods for multiport handset antennas

Figure 3.7. CMA results for an unbroken metal rim. (a) Eigenvalues for the two lowest modes and modal current distributions at the resonance frequency for (b) mode 1 and (c) mode 2. [III]

whole 0.7–0.96GHz band and mode 2 in the narrower 0.824–0.96GHz band to enable two-element MIMO operation. The modal current distributions shown in Figs. 3.7b–3.7c can be used as the starting point for designing exciter elements. The first mode is excited with antenna elements placed near the current minima at the opposite ends of the device. Similarly, the second mode is excited with elements near the current minima on the long edges. To leave space for the MHB and HB elements, the two elements for mode 2 are placed on one of the long edges and the elements for higher frequencies on the other.

The final antenna structure was designed on the basis of this starting point. Fig. 3.8 shows the simulation model of the designed antenna and the measured prototype. The exciter elements are inverted L-shaped coupling elements placed in the space between the ground plane and the metal rim. Due to the non-resonant nature of these elements, matching networks are also required to make the antennas resonate properly in the desired frequency ranges. The resulting S-parameters in Fig. 3.9 show that the couplings between the elements forming a cluster (e.g., $S_{21}$ and $S_{43}$) are high and that those with elements in other clusters (e.g., $S_{31}$, $S_{32}$, $S_{41}$, and $S_{42}$) are low. The simulated matching efficiencies shown in Fig. 3.10 demonstrate that a high coupling is not detrimental like in traditional single-feed antenna systems. A matching efficiency higher than 50% is achieved in the two LB frequency ranges as well as in a very wide frequency band starting from around 1.5GHz up to 4GHz. Two different ways for utilizing the elements in a multiport operation can also be identified: using elements with a similar frequency response, as seen in the LB operation, or combining elements with different frequency responses to cover wider frequency bands, as seen at higher frequencies.

Fig. 3.11 presents the resulting total efficiencies. It can be seen that LB cluster
Design methods for multiport handset antennas

Figure 3.8. (a) Simulation model of an antenna with elements of each cluster marked with the same color and (b) measured antenna prototype. [II]

Figure 3.9. Simulated and measured S-parameters for (a) LB and (b) HB. [II]

Figure 3.10. Simulated matching efficiencies of clusters and individual antenna elements. [II]
1 achieves an efficiency higher than 40% and cluster 2 achieves an efficiency higher than 20%. At higher frequencies, an efficiency of 25–80% is achieved in the very wide 1.56–4 GHz band. The ECC, as shown in Fig. 3.12a, is mostly below 0.2, and the maximum is about 0.5, indicating good potential for MIMO operation. Particularly in the LB, at which the largest benefits can be achieved from the CMA, the ECC is below 0.1. Fig. 3.12b shows the calculated capacities. It can be seen that the 2×2 MIMO capacities are in the range of 7.3–9.8 bits/s/Hz, corresponding to 65–87% of the ideal 2×2 capacity. Compared to other published designs with unbroken metal rims, these results show very good performance. Typically, larger ground clearances are used, the LB antennas cover only the 824–960 MHz band, and the HB is not included at all.

This chapter outlined different methods for utilizing multiport antenna tech-
Design methods for multiport handset antennas. Depending on the limitations set by the platform, in this case, for example, an unbroken metal rim or a rim with slots, multiport antennas with different properties can be designed. In [I], wide frequency bands can be covered with a large number of MIMO antennas, but several slots are required in the rim. In [II], a more challenging, but visually and mechanically more appealing, continuous metal rim can be effectively utilized. Compared to traditional antenna solutions, using multiport techniques provides benefits in both cases and helps achieve good results in terms of antenna performance.
4. Adaptive operation and user effect with multiport antennas

Although handset antennas are most often designed to operate in free-space conditions, they are normally not used as such. The operation environment (e.g., the device being held by the user in hand or next to the head) can have a large impact on the operation of the antennas. Generally, the user effect almost always significantly reduces the efficiency of the antennas and, in worst-case scenarios, can completely destroy the operation. Hence, different methods for reducing this negative effect caused by the user have been studied over the years [186]. Such methods included, for example, dynamically choosing the least affected antennas from a larger set of identical antennas [187]–[189] and antenna shielding, in which one of two identical antennas is actively used while the other acts as a shield [190], [191]. While these techniques have been shown to be effective in reducing the user effect, applying them has become more and more difficult in newer designs, in which the space reserved for the required additional structures has become smaller.

In this chapter, it is first shown that the antenna cluster technique can be used to reduce the negative user effect effect [III], [IV]. Then, a hand-immune handset antenna design from [V] is presented.

4.1 Reducing user effect using multiport techniques

Because of the frequency-reconfigurable feeding weights used in the antenna cluster technique, it is possible to utilize these to change the operation of a cluster for different operation environments (e.g., free space and the user’s hand holding the device). To study this, the two multiport antenna designs from [I], [II], shown in Fig. 4.1, were used in [III], [IV]. Both antennas were measured using a Speag SHO3T0110-V3RWC hand phantom, with electrical and mechanical properties similar to an average human hand, also used in standardized testing [192]. Using the measured far-field patterns, the feeding weights can be re-optimized using (2.22) and (2.23) from Section 2.5 to take into account the hand and achieve an optimal performance both in free space and with the user.
Adaptive operation and user effect with multiport antennas

Figure 4.1. (a) Unbroken metal rim antenna and (b) a switch-reconfigurable antenna prototype with a hand phantom. [IV] © 2020 EurAAP

Figure 4.2. (a) Measured total efficiencies and (b) calculated MIMO capacities in free space and with a hand phantom for the antenna in Fig. 4.1a. [III] © 2019 IET

Fig. 4.2 shows the total efficiencies and calculated MIMO capacities for the unbroken metal rim antenna in Fig. 4.1a for three different cases: in free space, with the hand phantom with free-space feeding weights, and with the hand phantom and re-optimized feeding weights. The results show that, particularly in the LB frequencies, re-optimization of the feeding weights can be used to
Adaptive operation and user effect with multiport antennas compensate for the degradation in performance due to the hand. For data stream 1, the efficiency can be improved by up to 65%. For different antenna clusters, the effect of the hand differs depending on the excited current distributions and the location of the antenna elements with respect to the hand. For example, LB stream 2 is much less affected than LB stream 1 because of the current maxima along the short edges of the rim where the hand is not holding the device. Because both elements of cluster 2 are affected in a similar manner, re-optimization does not offer much improvement, whereas the elements of cluster 1 are more differently affected, making it possible to utilize re-optimization.

The difference in how much re-optimization affects the results of each cluster can also be understood by looking at both the original and the re-optimized feeding weights in Fig. 4.3. For LB stream 1, the power balance is significantly changed, as well as the phase difference adjusted, leading to an improved efficiency. For LB stream 2 and the MHB and HB antennas, the free-space and

![Graphs showing amplitude and phase vs. frequency for different feeds.](a)

![Graphs showing amplitude and phase vs. frequency for different feeds.](b)

![Graphs showing amplitude and phase vs. frequency for different feeds.](c)

**Figure 4.3.** Free-space and re-optimized feeding weights for (a) LB data stream 1, (b) LB data stream 2, and (c) MHB and HB data streams for the antenna in Fig. 4.1a. [III] © 2019 IET

45
optimal weights are very close to each other.

In addition to the improvements achievable with adjustable feeding, it is also important to pay attention to the results in general. Although additional benefits may not be gained for all antenna clusters, multiport antennas with distributed exciter elements can still achieve good performance with the user. On average, a total efficiency higher than 23% is achieved for the LB, reaching almost 30% for higher frequencies. Moreover, the MIMO capacity is better than what can be achieved with ideal single-antenna systems even in free space throughout the whole frequency band. With unbroken metal rims, two-element MIMO, and wide operational bands, these can be considered as good results.

![Total efficiency graph](image1)

*Figure 4.4. Measured total efficiencies for (a) LB streams 1 and 2, (b) MHB and HB streams 1 and 2, and (c) MHB and HB streams 3 and 4 in free space and with the hand phantom for the antenna in Fig. 4.1b. [IV] © 2020 EurAAP*

The total efficiencies and MIMO capacities achieved with a similar procedure for the switch-reconfigurable multiport antenna in Fig. 4.1b from [I] are presented in Figs. 4.4 and 4.5. In this case, the results show that re-optimization can improve the efficiency in comparison to the original feeding weights. Again, the largest improvement can be seen in the LB. An up to threefold increase
Adaptive operation and user effect with multiport antennas

Figure 4.5. MIMO capacities calculated from the measurement results for the (a) LB and (b) MHB and HB for the antenna in Fig. 4.1b. [IV] © 2020 EurAAP

Figure 4.6. Efficiency of the cluster and individual elements for LB stream 1 and feeding signal amplitudes for the antenna in Fig. 4.1b. [IV] © 2020 EurAAP

can be achieved, and an average efficiency of 23% is achieved for the whole LB. In terms of capacity, this corresponds to a maximum increase of about 20%, compared to the original feeding weights. In this case, a larger difference can also be observed at higher frequencies. For example, the efficiency of MHB stream 1 drops to below 10% with original weights but can be kept above 20% with the optimal weights. In this case, the way the elements are distributed around the rim is the main factor affecting how the hand affects the performance of the antennas. It should be noted that a better than ideal SISO capacity for the LB and a better than ideal 2x2 MIMO capacity for the MHB and HB are achieved with the user.

Fig. 4.6 shows the individual element efficiencies and cluster efficiencies along with the feeding amplitudes for LB stream 1. In free space, the two elements are used to cover the lower and higher ends of the band, and similarly the feeding amplitudes are adjusted accordingly. With the hand phantom, the efficiency of port 4 becomes much worse than that of port 1, and therefore a better efficiency for the cluster is achieved when the power balance is adjusted for this.

It is not possible in practise to directly have the information on the radiation
patterns used here to re-optimize the feeding weights. For practical realization, different options would need to be considered. One option could be to measure the antenna performance in different use scenarios (e.g., different hand positions), and gather a set of different feeding weights. Then based on the information available to the device (e.g., information from a set of sensors or based on the data transfer rate), different weights could be applied to maximize the performance.

In conclusion, the results of this section show that multiport antenna designs can retain good performance with the user’s hand although this was not taken into account in the design process. In addition, it was demonstrated that it is possible to utilize the reconfigurability of the feeding weights to adapt the operation for changing operation environments or different use cases, in this case to compensate for the performance degradation caused by the user. The actual benefit that this offers depends mainly on two factors: how the elements of the clusters are distributed around the device and how the user’s hand affects each of the elements. To obtain the maximum benefit, both of these factors should be taken into account in the design process.

4.2 Designing hand-immune multiport antennas with characteristic mode analysis

Given the promising results in the previous section on multiport antennas and the user effect, the next goal was to take the user into account from the beginning of the design process to design hand-immune handset antennas. To do this, in [V], CMA was utilized to analyze the properties of the combination of the metallic antenna and the user modeled as lossy dielectric. This mode analysis is combined with adaptive multiport feeding arrangement to excite the preferred modes properly.

Recently, the CMA has been extended for the combination of PEC and lossy dielectric structures [87], [88]. With the correct formulation of the eigenvalue problem, modal solutions have physically meaningful interpretations. For example, the real and imaginary parts of complex eigenvalues describe the loss power and reactive power:

$$\text{Re}(\lambda_n) = \frac{P_{\text{reac}}}{P_{\text{rad}}}, \quad \text{Im}(\lambda_n) = \frac{P_{\text{loss}}}{P_{\text{rad}}},$$

(4.1)

where $P_{\text{reac}}$ is the reactive power stored in the near field, and $P_{\text{loss}}$ is the loss power for mode $n$. Other useful parameters include the modal efficiency,

$$\eta_n = \frac{1}{1 + \text{Im}(\lambda_n)} = \frac{P_{\text{rad}}}{P_{\text{rad}} + P_{\text{loss}}},$$

(4.2)
Adaptive operation and user effect with multiport antennas

Figure 4.7. Antenna structure with a ground plane and a broken rim used for CMA with the user. [V]

Figure 4.8. Modal significance for the structure in Fig. 4.7 (a) without the hand and (b) with the hand. [V]

and the modal coupling parameter,

$$\kappa_n = \frac{\text{Re}(\eta_{02}) \int_{S_D} \| \mathbf{J}_n \|^2 dS + \frac{1}{\text{Re}(\eta_{02})} \int_{S_D} \| \mathbf{M}_n \|^2 dS}{\text{Re}(\eta_{01}) \int_{S_C} \| \mathbf{J}_n \|^2 dS},$$  \hspace{1cm} (4.3)

calculated from the electric and magnetic current densities, $\mathbf{J}_n$ and $\mathbf{M}_n$, on surfaces $S_C$ and $S_D$ of the PEC and dielectric structures, respectively. The modal efficiency provides the highest radiation efficiency obtainable for mode $n$, whereas the modal coupling parameter defines the ratio of the modal currents on the PEC part and dielectric part. Large values indicate stronger currents on the dielectric, a value of one means equal currents, and small values indicate dominating currents on the PEC part.

To achieve user-immune operation, a structure that can support several resonating modes with good radiation properties, both with the user and in free-space operation, is needed. This can be realized by having properly designed sections in the metal rim. Fig. 4.7 shows an antenna structure consisting of a ground plane and a three-section metal rim, with a total size of $150 \times 75 \times 5 \text{mm}^3$ and ground clearance of only 2mm, used for modal analysis. Fig. 4.8 shows modal significance in free space and with the hand, and Fig. 4.9 shows modal
Adaptive operation and user effect with multiport antennas

![Modal efficiencies](image)

**Figure 4.9.** Modal efficiencies for the structure in Fig. 4.7. [V]

![Modal electric currents](image)

**Figure 4.10.** Modal electric currents for (a) mode B1 at 770MHz, (b) mode B2 at 900MHz, and mode B3 at 885MHz. [V]

Efficiencies with the hand. The results reveal two to three modes with promising properties in the LB frequency range. To see whether these modes can be effectively excited, the surface currents of the first three modes are shown in Figs. 4.10 and 4.11. Modes B2 and BH2 are mostly due to the fundamental mode of the ground plane, whereas modes B1 and BH1 have the strongest currents on the right-side L-shaped section of the rim and modes B3 and BH3 have the strongest currents on the left-side L-section. It should be noted that very similar current modes exist both for free-space operation and with the user, suggesting that they may be used for user-immune operation. The modal coupling parameters for only a ground plane and broken rim structures with the hand are shown in Fig. 4.12. These results confirm that, compared to the traditionally used ground-plane modes, the modes of a properly designed metal rim structure produce significantly lower coupling to the modes of the hand, therefore reducing the negative user effect.
Next, a set of collaboratively used exciter elements were designed. Generally, while designing these types of systems, it is important to include the antenna element design, matching network optimization, and adaptive feeding signal optimization into the same procedure. This can be done by optimizing the matching components using the far-field patterns simulated with the hand. Including the effect of the components into the radiation matrix $D$ allows calculating the optimal feeding signals. In addition, utilizing a proper numerical optimization algorithm (e.g., the genetic algorithm) allows simultaneously optimizing the matching networks and feeding signals. Fig. 4.13 shows an antenna structure...
with three elements and the optimized matching networks. Fig. 4.14 shows the S-parameters and feeding amplitudes and weights, and Fig. 4.15 shows the resulting total efficiencies of the individual elements and combined operation of the cluster. Using the first and second elements, the higher and lower parts of the band are covered with the third element supporting the operation, for example, by affecting the coupling between the elements. The results show that a total efficiency higher than 30% can be achieved across the 750–960MHz band. With the combined and adaptive excitation of several of the modes, a wider frequency band can be covered with a better efficiency than what can be achieved with traditional single-feed solutions.

The design of Fig. 4.13 was used as a starting point for a more realistic realization. First, because the third LB element played mainly a supporting role, it was not used as an actively fed element in the LB cluster. Instead, it was utilized as an individual element for the 3.3–3.8GHz HB but designed simultaneously with the LB to allow its use also in controlling the coupling of those elements. In addition to the 0.7–0.96GHz LB, the first two ports were also
Adaptive operation and user effect with multiport antennas

Figure 4.15. Individual element and combined cluster total efficiencies for the antenna structure in Fig. 4.13. [V]

<table>
<thead>
<tr>
<th>Stream</th>
<th>Port 1</th>
<th>Port 2:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream 1</td>
<td>0.7-0.96 GHz</td>
<td>1.7-2.7 GHz</td>
</tr>
<tr>
<td>Stream 2</td>
<td>1.7-2.7 GHz</td>
<td>3.3-3.8 GHz</td>
</tr>
<tr>
<td>Stream 3</td>
<td>Port 3:</td>
<td>3.3-3.8 GHz</td>
</tr>
<tr>
<td>Stream 4</td>
<td>Port 4:</td>
<td>3.3-3.8 GHz</td>
</tr>
</tbody>
</table>

Figure 4.16. (a) Covered frequency bands and the corresponding element placement and metal rim structure. (b) Simulation model of the proposed antenna structure. [V]

extended to cover the 1.7–2.7GHz MHB and 3.3–3.8GHz HB. For additional MHB and HB MIMO antennas, the unused U-shaped section of the rim at the other short end of the device was divided into three sections: two corner sections and one parasitic element in the middle. The larger of the corner sections was used for the MHB and HB antenna, whereas the smaller one was used for HB only. Because the modes studied earlier had practically zero current in this part of the rim, these modifications did not affect the LB operation. Fig. 4.16a presents the division of the rim, placement of the elements, and the covered frequency bands for these, and Fig. 4.16b shows the simulation model of the antenna.

Fig. 4.17 shows the final matching networks and antenna prototype with the hand phantom. Fig. 4.18 shows the total efficiency results and calculated MIMO capacities with the hand phantom. The results show a total efficiency of about 30–50% in the LB, 20–65% in the MHB, and 24–83% in the HB. The capacity achieved was about 80% of the corresponding ideal capacity in all bands. Fig. 4.19 shows simulated capacities in free space and for some additional cases. The effect of the main internal components (i.e., the battery and display panel, as shown in the upper part of the figure) and the difference between the right- and left-hand grips were also studied. The results prove that the differences between different hand grips and free-space operation are small and that the
Adaptive operation and user effect with multiport antennas

Figure 4.17. (a) Realized matching networks and (b) an antenna prototype with the hand phantom. [V]

Figure 4.18. (a) Measured and simulated total efficiencies with the hand phantom. (b) MIMO capacities calculated from the measured and simulated radiation patterns. [V]

The proposed design is hand-immune, hence meeting the design goals. It was also found that the effect of the internal components is small.

It can be concluded that the proposed method combining the modal analysis for the antenna and the lossy user can be effectively used to design handset antennas that are almost completely immune to the effect of the user. Despite the extremely small clearance of only 2 mm, three wide frequency bands, and MIMO operation, very good performance can be achieved with the user's hand.
holding the device. Although traditional antenna designs might exhibit a better efficiency in free space, their performance degrades much more with the user, leading in some cases to a very poor efficiency, below 10%.

In addition to the hand-immune design method presented in [V], the CMA has also been recently used to reduce the negative user effect in [85]. Comparing the radiation patterns of an antenna with and without the hand and the characteristic patterns of a similar structure without any specific feeding allows finding robust radiation patterns. Although the modal analysis itself does not include the user and the method requires antenna structures with feeding, an improved performance was achieved. These examples show that CMA is an effective design tool for robust handset antennas.
5. **Multiport antennas and bandwidth challenges**

One of the major challenges with modern handset antennas is achieving a wide bandwidth with the very strict physical limitations of antennas. Multiport techniques with adaptive feeding, as presented in the previous chapters, offer one way to improve the performance of handset antennas. However, with the need to create antennas for increasingly difficult environments, other types of tunability are required. In addition, with multiport antennas, the number of factors affecting the antenna performance increases, further complicating the design process. Therefore, to overcome these new design challenges, effective design tools are required.

In the first part of this chapter, the use of both multiport feeding and tunable matching networks are studied to enable the utilization of new and challenging locations for antennas inside smartphones [VI]. In the second part, a new design tool, which can significantly accelerate the design process of multiport antennas, based on the Q-factor is presented [VII].

### 5.1 Extremely low-profile antenna for challenging environments in handsets

The current LB and MHB as well as the increasing number of HB MIMO antennas are practically always realized in the fully occupied metal rim structure of smartphones. Only very challenging locations, such as a small gap between the battery and the back cover, are left for new types of antennas. As shown in [VI], by combining multiport feeding with tunable matching components, extremely low-profile antennas with good performance can be realized in these previously unutilized locations.

The major challenge with these new types of antennas is that they should have a very low profile to allow placing them, for example, behind the back cover or on top of the battery. While many published designs have been considered to have a low profile [177], [180], [181], [193]–[195], they are often considered to be still too large for modern smartphones, in which heights of less than 1 mm are available. Furthermore, they are often difficult to integrate into realistic...
device models, and the whole 3.3–4.2GHz band is often not covered. To make use of the existing volume inside the device, it is important to take advantage of the volume between the battery and the glass back cover. Fig. 5.1 shows a comparison of the traditional patch antenna and the proposed antenna. Given the possible battery expansion and manufacturing tolerances, among other reasons, a certain empty space around the battery is needed. By integrating the main radiator into the back cover and exciting the radiation modes with non-contacting elements from the sides, this volume can be efficiently utilized. This allows increasing the effective size of the antenna while keeping the required physical volume the same as in traditional solutions. In addition, there is no need for separate antenna PCBs on top of the battery, and the feeding elements and matching networks can be placed on the main PCB of the device along with other components.

Both the design process and operation principles are studied with the antenna model shown in Fig. 5.2. The main radiator is placed on top of the aluminum main body and battery, on the bottom surface of the glass back cover, with only a 0.75mm gap between the battery and the back cover. Two IFA-type exciter elements are placed on the long and short edges of this metallic patch, with a slot cut in the middle of the patch. Fig. 5.3 shows the S-parameters for this two-port antenna as well as for a single-port reference case. The results show that, by introducing the second element, a new resonance is created between the two resonances of the single-feed case. To better understand the operation mechanism of this structure, the surface currents for three different slot sizes with two feeds and the single-feed reference are shown in Fig. 5.4. With one
Multiport antennas and bandwidth challenges

Figure 5.3. S-parameters of the two-port antenna in Fig. 5.2 and the one-port reference structure. [VI]

<table>
<thead>
<tr>
<th>Structure</th>
<th>Resonance 1st</th>
<th>Resonance 2nd</th>
<th>Resonance 3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: 0.5x11 mm²</td>
<td><img src="image1" alt="image" /></td>
<td><img src="image2" alt="image" /></td>
<td><img src="image3" alt="image" /></td>
</tr>
<tr>
<td>2: 0.5x20 mm²</td>
<td><img src="image4" alt="image" /></td>
<td><img src="image5" alt="image" /></td>
<td><img src="image6" alt="image" /></td>
</tr>
</tbody>
</table>

Figure 5.4. Surface currents for dual-feed antennas at different resonances with three different slot sizes and a single-feed antenna. [VI]

Feed, only current distributions along the longer dimension of the patch are excited; however, with two feeds, a new mode with a strong diagonal component is excited. Because the slot length mainly affects this diagonal mode, it can be used to tune the frequency of the second resonance without significantly affecting the first or third resonance, while the width of the slot mainly affects the first and third resonance frequencies.

Figure 5.5. Two-port antenna cluster and tunable matching circuit topology. [VI]

To cover the full frequency band, matching networks and some tunability are required. In this case, both frequency-reconfigurable feeding weights and tunable matching networks, as shown in Fig. 5.5, are utilized. Similarly, as in the matching network optimization presented in Section 4.2, it is important to include all the separate elements (i.e., fixed components, tunable components, and feeding weights) into the same optimization process to optimize their combined operation. In real use, a certain instantaneous bandwidth with fixed tunable elements needs to be covered. The largest bandwidth for the HB is...
100MHz, and therefore the full frequency band is divided into nine 100MHz wide sub-bands with fixed tunable element values. In addition to frequency tuning, these tunable elements can be used to adapt the operation for different environments, for example, changes in the structure near the antenna or the user effect. One possible change that can occur with real use is the swelling of the battery. Therefore, the effect of increasing battery height and its compensation with tunable elements have been studied in [VI]. The user effect results are discussed later in this section.

Figure 5.6. (a) S-parameters, (b) TARC, and (c) total efficiencies for the antenna in Fig. 5.2 with a gap of 0.75mm. [VI]

Figs. 5.6a and 5.6b show the tuned S-parameters and TARC. For multiport antennas, TARC corresponds to the traditional reflection coefficient of single-feed antennas and is, therefore, used to describe the operation of multiport antennas. These results demonstrate that, with the combination of matching networks and complex feeding weights, a proper level of coupling, in addition to matching, is achieved, leading to a total reflection better than −7 dB on the whole band. It can be seen that the total efficiency in Fig. 5.6c is better than 40% with ideal tunable capacitors and that more realistic Q-based capacitors, with similar properties to those of real components, decrease the minimum
efficiency by only about five percentage points on average. The efficiency results for the different battery heights with and without adaptivity in Fig. 5.7 show that tunable elements can also be used effectively to reduce the performance degradation resulting from the decreasing gap between the battery and the back cover. Without the adjustment of the tunable elements, the minimum efficiency drops down to 16%; however, with the adjusted values, an efficiency better than 30% can be retained.

Next, this initial design was extended into a fully realizable structure. The final antenna structure is presented in Fig. 5.8, with a more detailed description available in [VI]. Tunable capacitors are realized with varactor diodes. Fig. 5.9 shows the final matching circuit topology and component values, and Fig. 5.10

Figure 5.7. Compensation of the degradation of efficiency due to increasing battery height with tunable element adaptivity. [VI]
Multiport antennas and bandwidth challenges

![Image of multiport antennas and bandwidth challenges](image)

Figure 5.9. Optimized matching networks for the antenna in Fig. 5.8. [VI]

![Graph showing total efficiency vs. frequency](image)

Figure 5.10. Simulated total efficiencies of the antenna structure in Fig. 5.8. [VI]

shows the resulting total efficiency results. Notably, the results prove that an efficiency better than 30% can be achieved with the extremely small gap of only 0.75 mm.

It is also possible to extend the proposed multifeed antenna for MIMO operation. Fig. 5.11a shows the possible 2×2 and 4×4 MIMO configurations. Although the main radiators in the back cover are placed relatively close to each other, the coupling between the feeds of different clusters is below −20dB in all cases.

![Graph showing calculated capacities](image)

Figure 5.11. (a) Possible MIMO configurations and (b) calculated capacities. [VI]

![Graph showing total efficiencies](image)

Figure 5.12. (a) Antenna and hand models used to study the user effect. (b) Total efficiencies with original free-space and optimal tunable elements. [VI]
Fig. 5.11b shows the capacities for these three cases. All of the cases achieved about 78% of the corresponding ideal capacity, which also demonstrates that increasing the number of MIMO antennas does not decrease the performance of the individual antennas.

As discussed in Chapter 4, the user effect is very important in practical use. Fig. 5.12a shows a simulation model for studying the user effect of this low-profile design. Fig. 5.12b shows the efficiencies of these two antennas with the original free-space tunables and re-optimized tunables. With re-optimization, up to 50% and 40% improvements can be achieved at best for antenna 1 and antenna 2, respectively. For these two antennas, it can be seen that the decrease in efficiency due to the hand is different. The efficiency of antenna 2 is more degraded, which can be explained using the radiation efficiencies and TARCs shown in Fig. 5.13. These results show that the difference in the radiation efficiency is not that large, while the difference in TARC is more evident. It should be noted that the TARC of antenna 1 is quite similar to free-space TARC; however, for antenna 2, the matching is actually significantly improved. Because of this, antenna 2 has a better efficiency than that of antenna 1. In addition, an equal or even slightly better efficiency than that achieved with free-space operation can be achieved in the 3.6–3.9GHz band.

Finally, the operation of the proposed antenna design was confirmed with measurements of the prototype shown in Fig. 5.14. It can be seen that the measured efficiencies in Fig. 5.15 correspond well with the simulated ones in Figs. 5.10 and 5.12b. Average efficiencies of about 35% in free space and 25% with the hand phantom have been achieved. These results confirm that, with the developed tunable multifeed technique, antennas with good performance can be realized in very challenging locations in smartphones with extremely small heights available for the structure.

As already mentioned in Chapter 4, the re-optimization of the tunables re-
Multiport antennas and bandwidth challenges

Figure 5.14. Prototype (a) with an open back cover and (b) with the hand phantom used. [VI]

![Prototype images](image1)

![Prototype images](image2)

Figure 5.15. Total efficiencies of the prototype in free space and with the hand phantom. [VI]

requires information on the far-field radiation properties which is not directly available in practice. Different options for realizing this re-optimization exist. First, some kind of knowledge on the operational environment is needed. This could be done based on information from sensors monitoring the proximity of the user, or by monitoring, for example, the levels of received power of the transceiver circuits or data transfer rates. Then, one option could be to collect a set of settings for the tunable elements based on the performance in different environments and choose different options from these to maximize the performance. Other option could be to utilize some appropriate optimization process to vary the tunable elements so that the best possible performance is achieved in different environments. Naturally, this optimization process should be done such that the achievable benefits are larger than the cost, for example, in terms of power usage. This requires more expertise than just that of the antenna designer and has not yet been studied in more detail in the context of this work. However, for realizations of this kind of adaptive antenna systems in actual products, this is an important aspect that should definitely be studied more in the future.
5.2 Multiport Q-factor and bandwidth estimation

Multiport antenna systems provide designers with new degrees of freedom that allow reaching a better performance than what is possible with traditional single-feed solutions. For example, by using multiple feeds, relatively high levels of coupling can be utilized for benefit. In addition, new types of current distributions can be excited with the collaborative use of feeds. This, however, also creates new challenges. When the antenna structure and feeding elements, matching networks, and frequency-dependent complex feeding weights all have a significant effect on the achievable bandwidth, the design and optimization problem often becomes very complicated and the design process becomes very time-consuming. Therefore, new tools for estimating the bandwidth performance of multiport antennas are needed to accelerate this design process.

As mentioned in Chapter 2, the Q-factor has long been used to measure the bandwidth and its limits for electrically small antennas. As discussed in [VII], Q-factor is still a topic of active research. Despite the first works being published already decades ago, new methods to calculate the Q-factor have been published relative recently, for example, in [196]–[198]. Also, the search for optimal currents in terms of Q [199], lower bounds of Q [200], minimization of Q [201], and tradeoffs between Q and other antenna parameters, such as radiation efficiency or directivity [202], [203], have been been topics of publications in recent years. Although it is still an active research topic especially in the computational EM community, it is also known to have limitations, especially with wide-bandwidth and multiresonant antennas [9], [204]. Partly for these reasons, modern antenna designers have not found many practical applications for the Q-factor.

Several different ways for calculating or approximating the Q-factor exist. The most common ones are the field-based and impedance-based Q-factors. The field-based Q-factor is calculated from the stored electric and magnetic energy, $W_e$ and $W_m$, and the radiated power as follows [201]:

$$Q = 2\omega \frac{\max(W_e, W_m)}{P_{rad}}. \quad (5.1)$$

Using the MoM matrix $Z^{MoM} = R^{MoM} + jX^{MoM}$ and the surface current density on the antenna surface $J$, this can be calculated as

$$W_e = \frac{1}{8} J^H \left( \frac{\partial X^{MoM}}{\partial \omega} - \frac{X^{MoM}}{\omega} \right) J, \quad W_m = \frac{1}{8} J^H \left( \frac{\partial X^{MoM}}{\partial \omega} + \frac{X^{MoM}}{\omega} \right) J, \quad (5.2)$$

with

$$P_{rad} = \frac{1}{2} J^H R^{MoM} J. \quad (5.3)$$

This field-based Q-factor, however, has a couple of challenges. First, it requires the MoM matrix and, therefore, cannot be easily used with most of the commercial EM simulators. Second, this matrix and its derivatives can be very large matrices for complex antenna structures, leading to computationally demanding
Multiport antennas and bandwidth challenges

calculations. The second option is to use the input impedance of an antenna to approximate the Q-factor. For a multiport antenna, the Q-factor is \[ Q_{ZM} = \frac{\omega |I^H R I + j(I^H X I + |I^H X I|/|\omega|)}{2I^H R I}, \quad (5.4) \]

where \( Z = R + jX \) is the impedance matrix and \( I \) is a vector of port input currents.

As we have seen with the multiport antenna designs presented in this work, the feeding signals play an important role in the optimal operation of the system. In the same way as for antenna efficiency, these complex feeding weights also affect the Q-factor. Because the weights maximizing the efficiency do not necessarily minimize the Q-factor, there is a need for a method to choose these weights correctly if the minimum \( Q \) for a multiport structure is to be found.

For the process to be computationally efficient, a formula in the form of a general Rayleigh quotient, \[ \frac{I^H MI}{I^H NI}, \quad (5.5) \]
is sought. It should be noted that the impedance-based Q-factor of (5.4) cannot be written in this form; hence, some modifications or approximations are needed. Two different approaches are taken in [VII]. First, the effect of the term \( R' \) is often small and can be neglected. Therefore, we can write an approximation for the impedance-based Q-factor as

\[ Q_{ZM}^{(1)} \approx \frac{\omega |I^H X I| + |I^H X I|/|\omega|}{I^H R I}. \quad (5.6) \]

Now, the feeding weights minimizing the Q-factor can be solved as an eigenvector corresponding to the minimum eigenvalue:

\[ \min \left\{ \text{eig} \left( X' \pm \frac{1}{\omega} X, R \right) \right\}, \quad (5.7) \]

where both options for the sign of the second term are evaluated and the correct one is then chosen. The second proposed modification is to consider each of the three terms in the numerator of (5.4) separately to obtain an upper limit for the Q-factor:

\[ Q_{ZM}^{(2)} \approx \frac{\omega |I^H R I| + |I^H X I| + |I^H X I|/|\omega|}{I^H R I}. \quad (5.8) \]

This can also be solved efficiently with a set of eigenvalue equations:

\[ \min \left\{ \text{eig} \left( \pm R' \pm X' \pm \frac{1}{\omega} X, R \right) \right\}. \quad (5.9) \]

To compare these approximations and the field-based and impedance-based Q-factors, Fig. 5.16 shows an example of a four-port antenna structure in the size of a smartphone and the resulting Q-factors for the field-based \( Q \), impedance-based \( Q_Z \), and the two proposed approximations, \( Q_{ZM}^{(1)} \) and \( Q_{ZM}^{(2)} \), all with unit voltage excitation in all ports. The results show that the impedance-based Q-factors agree well with the field-based Q-factors and that the proposed approximations provide fairly accurate results.
Multiport antennas and bandwidth challenges

Figure 5.16. (a) Example of a four-port antenna structure. (b) Q-factor results for different formulations. [VII]

Figure 5.17. (a) Symmetric structure of case 1 and (b) non-symmetric structure of case 2 for the Q-factor and matched efficiency evaluation. [VII]

In [VII], the Q-factor was used as a figure of merit to predict the actual realizable performance of a multiport antenna with optimized matching networks. This helped diminish the need for performing time-consuming numerical optimizations for a large number of different structures because it was possible to use the Q-factor to find the most potential cases first. The two-port antennas shown in Fig. 5.17 were studied first. The Q-factor for both of these cases was calculated from (5.4) by numerically optimizing the amplitudes and phases of the input signals to minimize $Q$ as well as the feeding signals that minimize the TARC (maximize efficiency). Three element matching networks were optimized for the 0.7–1.0GHz band to evaluate the actual performance of these two antennas. Fig. 5.18 shows the resulting Q-factors and matched efficiencies. It can be seen that both Q-factors are practically identical for the symmetric structure of case 1; however, for the nonsymmetric structure of case 2, the TARC-optimal feeding weights provide larger $Q$ than the Q-optimal weights. The efficiencies in both cases are practically identical. As Q-factors with optimal weights are very close to each other for cases 1 and 2, these results suggest that it is possible to predict the realizable performance from the Q-factor if the feeding weights are properly taken into account.

To demonstrate the benefits of these methods in a more practical application case, a simple design procedure for a two-port handset antenna is presented. As a starting point, a single-antenna element in the short edge of the ground plane
Multiport antennas and bandwidth challenges

Figure 5.18. (a) Q-optimal and TARC-optimal Q-factors and (b) efficiencies with matching networks for the antenna structures in Fig. 5.17. [VII]

Figure 5.19. (a) One-port reference antenna and (b) two-port antenna cluster used for studying the Q-factor and efficiency. All dimensions are in millimeters. [VII]

operating in the 0.7–1.0GHz band is shown in Fig. 5.19a. A second element, as shown in Fig. 5.19b, was added to the long edge, whose dimensions and placement should be optimized. Hence, a large number of combinations for the three parameters of element 2 were simulated. Then, matching networks were optimized for all of these structures, and finally Q-factors were calculated. Four different methods were used:

- Numerically optimized feeding weights from (5.4)
- TARC-optimal feeding weights from (5.4)
- Approximation $Q_{ZM}^{(1)}$ (5.6) with feeding weights from (5.7)
- Approximation $Q_{ZM}^{(2)}$ (5.8) with feeding weights from (5.9).
Multiport antennas and bandwidth challenges

Figure 5.20. Minimum matched efficiencies over the target band of 0.7–1.0GHz and the corresponding maximum and mean Q-values for (a) numerically optimized feeding weights and (b) approximation $Q^{(2)}_{ZM}$. [VII]

Fig. 5.20 presents the results for the minimum efficiency over the designed frequency band and maximum and mean Q-values, sorted on the basis of decreasing mean Q-value, for the numerical optimization of $Q_{ZM}$ and approximation $Q^{(2)}_{ZM}$. These results generally show a strong correlation between the matched efficiency and Q-values. There are a few data points at which small Q does not correspond to a high efficiency; other than these, a decreasing Q corresponds well with increasing efficiency. In addition, it was shown in [VII] that the Q-factor calculations are significantly faster than the matching network optimization. Optimizing the matching networks takes more than a day, even with a powerful workstation, whereas the Q-factor approximation takes less than a minute, even on a laptop computer. Therefore, the proposed Q-factor method can be used to predict the achievable performance of multiport antenna structures and

Figure 5.21. Two-element antenna clusters A, B, and C. [VII]
Multiport antennas and bandwidth challenges

![Graphs showing efficiency and Q-factors for multiport antennas]

**Figure 5.22.** (a) Efficiencies with matching networks and (b) Q-factors for the antenna structures in Fig. 5.21 and the reference antenna in Fig. 5.19a. [VII]

considerably accelerate the design process.

For a more insightful view, the Q-factors and matched efficiencies for the three different structures in Fig. 5.21 as well as the reference one-port structure in Fig. 5.19a are shown in Fig. 5.22. In addition to the relation between the Q-factor and efficiency, these can also be used to more generally demonstrate the benefits and properties of multiport antennas in comparison to their traditional single-feed counterparts. If improperly designed, the multifeed antenna can have worse performance than that of the reference (cluster C), no benefits may be gained (cluster B), and in an optimal case an improved performance (cluster A) can be achieved.
6. Summary of Publications

Publication I: “Switch-Reconfigurable Metal Rim MIMO Handset Antenna With Distributed Feeding”

This paper presents a new design method based on a multiport simulation model and an algorithm to evaluate the performance of a large number of different antenna structures efficiently. This method significantly accelerates the design process by transforming an EM problem into a circuit problem. A switch-based MIMO antenna system for a metal-rimmed handset with two-element MIMO capability in the LB and four-element MIMO capability in the MHB and HB is designed, manufactured, and measured using the proposed method.

Publication II: “Unbroken Metal Rim MIMO Antenna Utilizing Antenna Clusters”

This paper presents a multiport antenna design for a device with an unbroken metal rim based on CMA. With multiport antenna clusters, the inherently high coupling due to the rim can be utilized. Moreover, with mode analysis, the modes of the rim are excited separately to obtain good MIMO performance. A prototype with wide bandwidths of 0.7–0.96GHz and 1.56–4.0GHz and two-element MIMO in part of the low band and the whole higher band is designed and manufactured.

Publication III: “User effect on antenna cluster based MIMO antenna”

This paper presents the benefits of the multiport cluster technique in exciting the orthogonal modes of an unbroken metal rim and the use of reconfigurable feeding weights with the user effect. The results show that, using multiple exciter elements, the radiation modes are excited more efficiently than with a single feed. The results on the user effect show that multiport handset antennas
can retain good performance with the user's hand holding the device.

**Publication IV: “Reducing User Effect on Mobile Antenna Systems With Antenna Cluster Technique”**

This paper discusses the user effect and the use of adaptive feeding weights of antenna clusters in the reduction of the degradation of efficiency due to the user with the antenna designs from Publication I and Publication II. The results show that, depending on how the exciter elements are divided and their location with respect to the user's hand, re-optimization of the feeding weights can be used to reduce the negative user effect on some frequency bands with both of the studied antennas. In addition, it is shown that while the HB elements can also be used to realize higher-order MIMO systems with single-feed antennas, utilizing them as multiport clusters offers a higher efficiency over a wider bandwidth with the user.

**Publication V: “Designing Hand-Immune Handset Antennas with Adaptive Excitation and Characteristic Modes”**

In this paper, a hand-immune antenna system for handsets is designed using CMA for combined lossy dielectric and metallic antenna structures. Including the effect of the user's hand in the design process from the beginning allows finding such modes that have favorable radiation properties in the presence of the user and that can also be used under free-space conditions. Using adaptive multifeed excitation arrangement, these modes are efficiently excited, especially at low frequencies below 1GHz. A complete antenna system with 0.7–0.96GHz LB, 1.7–2.7GHz MHB with two MIMO antennas, and 3.3–3.8GHz HB with four MIMO antennas, which is almost completely immune to the presence of the user, is presented.

**Publication VI: “Extremely Low-Profile Tunable Multiport Handset Antenna”**

This paper presents a new antenna design with an extremely low profile for modern smartphones. Realizing the main radiator on the back cover on top of the battery allows utilizing the existing space inside the device. This increases the effective size of the antenna and, thus, improves its performance in comparison to traditional solutions. With multiple non-contacting exciter elements placed on the main PCB of the device, combined with tunable matching networks and adaptive feeding weights, the radiation modes of the back-cover radiator can be efficiently excited for the 3.3–4.2GHz band. In addition, these tunable elements
can be used to adapt the operation of the antenna to changing environments, for example, the battery swelling or the user’s hand holding the device.

**Publication VII: “Q-factor for Multiport Antennas and Achievable Bandwidth Estimation”**

In this study, a new design tool based on the quality factor $Q$ for multiport antennas is developed. By properly taking into account the frequency-dependent excitation signals, the minimum $Q$-factor is calculated. With the proposed approximations, this $Q$-factor can be calculated extremely fast. It is also shown that the $Q$-factor predicts the achievable performance of multiport antennas when the proper matching networks are applied. Because matching network optimization for multiport antennas is very slow in practice, this new $Q$-factor-based method can be used to significantly accelerate the design process.
7. Conclusions

This thesis focused on developing multiport antenna methods for handset antennas. The main scientific contributions include the development of new handset antenna designs and design tools as well as methods that can be used to realize multiport antenna systems for the challenging environments in modern handsets.

Publication [I] presented a new and effective design method for multiport antennas and an antenna for metal-rimmed handsets designed using the proposed method. By utilizing the metal rim of the device with switch reconfigurability, optimal antennas can be realized for different frequency bands. Moreover, with the proposed optimization algorithm, the optimal antenna structure can be found without the need for a large number of time-consuming EM simulations. In [II], a method for efficiently using an unbroken metal rim for MIMO antennas was presented with the proposed design method utilizing CMA to find the optimal modes of the rim and exciting them with multiple exciter elements for improved performance.

The effect of the user’s hand holding the device was first studied with the antennas designed primarily for free-space operation in [III]–[IV]. The results showed that multiport designs with antenna elements distributed around the device can retain good efficiency despite the user effect. It was also found that, in certain situations, the adaptivity of the feeding signals can be used to compensate for the losses due to the hand. As a next step, this was studied further in [V], in which a user-immune handset antenna was designed. With mode analysis, which takes the user into account from the beginning of the design process, modes with favorable radiation properties, both with the user and in free space, were first found, and then adaptive excitation arrangement was used to efficiently excite these modes.

In [VI], an antenna design with an extremely low profile to be integrated into the back cover of a device was presented. By combining the use of two exciter elements and both feeding signal adaptivity and tunable matching components, the volume (height less than 1mm) between the battery and the back cover can be utilized for antennas. To help designers accelerate the possibly time-consuming multiport design process, a new design tool based on the quality
factor was proposed in [VII]. Calculation of the Q-factor with proper feeding signals can be done extremely fast with the proposed approximations. It was also shown that this value estimates the actual performance of the device well without the need for slow matching network optimization with a large number of antenna structures.

This work has further developed the theory, applications, and design methods of multiport antennas. The main focus was on practical realizations that can help antenna designers reach the increasingly difficult goals set by both communication systems requirements, as well as the size, visual appearance, and device integrability, and other industrial requirements. The results that have been achieved during this study have shown new ways of utilizing multiport antennas for handsets and demonstrated benefits that can be achieved with these techniques. The most important ones, as seen by the author, are improvements in bandwidth and efficiency of these antennas and the possibility to adapt their operation for different operation environments, such as reducing the negative effect of the user or to compensate physical changes in the device where the antennas are placed. In addition, these techniques enable the utilization of previously unused places for new types of antennas. Besides finding new applications for multiport antennas, other important outcomes of this work have been the developed design tools and understanding of the design process of multiport antennas. The new degrees of freedom that the multiport techniques offer also mean that the design process becomes more complex than with traditional antennas. With the results of this work, many of these challenges are now better understood and effective design tools can also be used with multiport antennas.

Although the work outlined here has helped develop practical utilization of multiport techniques for handset antennas, there are still many things to be considered and further studied in the future. For example, using feeding signals to adapt the operation to different environments or changes in structures near the antennas would require a method for monitoring the operation and finding the optimal weights for each scenario from the information available for the system inside the device. Also, more thorough co-design and practical integration of multiport antennas and the required multichannel transceiver ICs are important topics for future research. Until now, the multiport techniques have mainly been utilized for sub-6GHz frequencies. With increasing interest in millimeter-wave antennas in smartphones, a natural question is, could similar multiport techniques also be applied at higher frequencies? Perhaps multiport techniques will also offer solutions to improve the performance of millimeter-wave antennas in the future.
References


Errata

Publication IV

In Fig. 5, the legend referring to "User with original weights" should read "User with optimal weights," and vice versa.
The increasing use of online-based services with modern smartphones requires faster wireless connections and better antenna systems. While these can be achieved with wider frequency bands and by increasing the number of antennas in multiantenna systems, the extremely limited volume available for the antennas and other practical limitations create great challenges for modern antenna designers. This thesis studies different ways of utilizing multiport antennas to improve the performance of sub-6 GHz handset antennas. New design methods for multiport antennas are developed and multiport antenna systems that can adapt their operation for changes in their operation environment are presented.