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Antennas for metal-covered handsets

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ABSTRACT OF THE MASTER'S THESIS

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This master's thesis studies the effects of a slotless, continuous metal cover of a mobile terminal on the performance of its antennas. Additionally, LTE MIMO antennas are designed together with GPS and Wi-Fi antennas. The cellular antennas should operate on 704–960 MHz and 1.71–2.69 GHz with at least 30 % efficiency, and the other antennas at 1.575 GHz, 2.4 GHz, and 5 GHz bands with 40 % efficiency.

The topic is studied by completing electromagnetic simulations. The used model of the mobile phone is much more accurate than the ones used in earlier studies. The simulations focus on the antenna structures, locations, and sizes, as well as feeding of them. Additionally, matching circuits are investigated, and designed for each antenna. The effect of the metal cover is studied with several test cases, each of which focuses on one parameter, e.g. a dimension, location, or feed of the antenna.

The first simulations are done with a simple model, and a concept for the cellular antennas is constructed on the basis of the obtained results. The final simulations are completed, and the antennas optimized with the accurate model. The proposed structure consists of three closely located, strongly coupling elements. The cellular antennas are at distinct ends of the device, and integrated into the side metals. GPS and Wi-Fi antennas are also integrated into the sides, and placed in the area between the ends of the phone.

The main challenge due to the metal-cover is obtaining sufficient and wideband matching. Regardless the challenging environment, all the designed antennas fulfill their requirements. Based on the results, achieving a good antenna performance in a metal-covered phone is not impossible.

Keywords: antenna, coupling, LTE, metal cover, MIMO, mobile phone

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Tässä diplomityössä tutkitaan matkapuhelimen yhtenäisen metallikuoren vaikutusta antennien suorituskykyyn. Työssä suunnitellaan myös LTE-taajuuksilla toimiva MIMO-antenni sekä GPS- ja Wi-Fi-antennit. Matkapuhelinantennien tulee toimia taajuuksilla 704–960 MHz ja 1.71–2.69 GHz vähintään 30 % hyötysuhteella. Vastaavasti muiden antennien taajuuskaistat ovat 1.575 GHz, 2.4 GHz ja 5 GHz tavoitehyötysuhteen ollessa 40 %.

Tutkimus suoritetaan sähkömagneettisilla simulaatioilla. Työssä käytettävä puhelimen simulointimalli on paljon realistisempi kuin aiemmissa tutkimuksissa käytetyt mallit. Simuloinnit keskittyvät antennirakenteisiin sekä niiden sijainteihin, kokoihin ja syöttötapoihin. Lisäksi jokaiselle antennille suunnitellaan sovituspiiri. Metallikuoren vaikutusta tutkitaan useilla eri testeillä, joista jokainen keskittyy yhteen parametriin kuten antennin mittoihin, sijaintiin tai syöttöön.

Työ aloitetaan yksinkertaisella simulointimallilla, ja näiden testien perusteella valitaan puhelinantennirakenne. Lopulliset testit ja antennien optimointi tehdään tarkalla mallilla. Esitetty rakenne koostuu kolmesta lähekkäin olevasta ja voimakkaasti kytkevästä antennielementistä. Puhelinantennit sijaitsevat laitteen eri päissä ja ovat osa puhelimen sivuissa olevaa metallirengasta. GPS- sekä Wi-Fi-antennit ovat myös osa metallirengasta ja sijaitsevat laitteen päätyjen väliin jäävällä alueella.

Suurin metallikuoresta aiheutuva haaste on riittävän hyvän ja laajakaistaisen sovitustason saavuttaminen. Vaikeasta ympäristöstä huolimatta suunnitellut antennit täyttävät asetetut suorituskykytavoitteet. Tulosten perusteella on mahdollista suunnitella hyvin toimivat antennit metallikuoriseen puhelimeen.

Avainsanat: antenni, kytkentä, LTE, matkapuhelin, metallikuori, MIMO

Preface

This master's thesis is the last piece of a puzzle called my studies. The last five months that I have used for this thesis are only a small portion of them. The past seven years have been one great experience, of which I regret nothing.

Since my time as a degree student is coming to an end, I would like to express my gratitude to several people. First, I would like to thank the supervisor of my thesis, Prof. Ville Viikari, for giving me the opportunity to work in his research group and study this interesting topic, for his constructive feedback, and for letting me work independently. This thesis is a part of a larger research project with AAC Technologies to whom I am thankful for funding this project. I am also grateful to my advisor, D.Sc. (Tech.) Anu Lehtovuori, for the discussions with her every day that inspired to look things differently, developed my thinking, and helped to finalize this thesis. Without her comments the contents of this thesis would have been a lot more challenging to digest.

During my time in Otaniemi, I have met more new people than I can count, and some of them will remain very good friends of mine. I would like to bring up two very important persons. Joel and Mikko have had a significant impact on my study time, and also have supported me a lot during the writing of this thesis, while they have been working on their own theses. Thank you. Friendships are not limited to individuals. I have been a member of so many wonderful groups during the years. Without them my study time would have been very boring. So thank you SIKH14, SIKH013, FTMK13, Neuvosto'14, HTMK12, SIK-fuksit13, EST IX, Tempaus2016 team, and Polytechnical Students' Museum.

The most supportive group without any questions is my family: mother Sirpa, father Matti, and little sisters Saila and Niina. For all my life, they have given me the freedom to do my own choices, of course asking to think twice about the strangest decisions.

Last but definitely not least, I would like to thank my beloved Anni, who deserves the sincerest gratitude, for her warmth, support, and understanding during this project, together with the weird moments that constantly cheer me up.

I hope the future students will enjoy their studies as much as I have. Jappadaida and Iuvenis in Aeternum!

Tekniikan kehdossa, 4.10.2016

Joni Kurvinen

Contents

Symbols and abbreviations

Symbols

c	speed of light $\approx 3 \times 10^8$ m/s
C	capacitance
$D(\theta, \phi)$	directivity at direction (θ, ϕ)
D_{max}	maximum directivity
E_θ	θ-component of electric field
f	frequency
$f(\theta, \phi)$	pattern factor
$F(\theta, \phi)$	(normalized) radiation pattern
$g(\theta, \phi)$	element factor
$G(\theta, \phi)$	gain at direction (θ, ϕ)
G	gain
L	inductance
l	antenna length
l_i	antenna length of element i
P_{in}	input power
P_{rad}	radiated power
Q	quality factor
R	resistance
R_o	ohmic losses
R_r	radiation resistance
R_s	source resistance
S_{ij}	scattering parameter to port i from port j
w	antenna width
X_a	antenna reactance
X_s	source reactance
x	Cartesian x-coordinate
y	Cartesian y-coordinate
Z_a	antenna impedance
Z_s	source impedance
z	Cartesian z-coordinate
Γ	reflection coefficient
η_{rad}	radiation efficiency
λ_0	free space wavelength
ϕ	azimuth angle
ρ_e	envelope correlation coefficient
θ	elevation angle

Abbreviations

3G	Third generation mobile network
4G	Fourth generation mobile network
CCE	Capacitive coupling element
DTC	Digitally tunable capacitor
ECC	Envelope correlation coefficient
EM	Electromagnetic
ESA	Electrically small antenna
GPS	Global Positioning System
HB	High band
IFA	Inverted F antenna
ILA	Inverted L antenna
ITU	International Telecommunications Union
LB	Low band
LTE	Long-Term Evolution
LTE-Advanced	Long-Term Evolution Advanced
MC	Matching circuit
MIMO	Multiple Input Multiple Output
MSA	Microstrip antenna
PCB	Printed circuit board
PEC	Perfect electric conductor
PIFA	Planar inverted F antenna
PILA	Planar inverted L antenna
RF	Radio frequency
Rx	Receiver
SNR	Signal-to-Noise Ratio
Tx	Transmitter
Wi-Fi	Trademark for WLANs
WLAN	Wireless Local Area Network

1 Introduction

The use of mobile devices have been growing rapidly for the last two decades, and the same trend will continue in the near future, as the global amount of mobile subscriptions is constantly increasing and applications are more and more data intensive [1]–[4]. Mobile phones are not anymore used for only traditional calls, but for communicating through a numerous different messaging services, social media, and other applications. Prior to the third generation mobile networks (3G), this have been impossible. 3G enlarged the channel bandwidth by the factor of 25 [5], which enabled significantly higher data rates.

After 3G, the standards of mobile communications have kept on evolving, as new applications and demands have been invented. In 2008, International Telecommunications Union (ITU) announced the new requirements for mobile networks [6]. Long Term Evolution (LTE), or the fourth generation mobile networks (4G), would again multiply channel bandwidth and data rates to answer the need for faster networks. However, LTE does not fulfill the specifications, but its successor LTE-Advanced will. 4G networks use over 40 frequency bands around the world [5], [7], and provide 1 Gb/s peak data transmission by utilizing techniques such as multiple input multiple output (MIMO) and carrier aggregation [8].

While the network standards have developed a lot, the mobile phones have changed their shapes several times [9]. Nowadays smartphones with large touchscreens are the common device. Large displays reserve a major amount of space for themselves, which sets different constraints for the placement of other subsystems. Modern mobile phones operate already on a wide range of frequencies, and it is estimated that the amount of communications systems might exceed 20 in the future [10]. This would mean 20 different antennas in a single device, which is quite a challenge for designers, as the network standards also demand a certain performance. In order to meet the requirements, antennas should operate on multiple bands or enable wideband communications [11].

Fortunately, antenna techniques are developing together with the networks. From long monopoles and dipoles sticking outside the handset, the antennas are currently inside the phone, or integrated into the housing of the device [5], [12]. Different forms of planar antennas have been a popular choice, since they are able to operate on multiple bands [13]. Although these antennas are designed to operate on multiple bands, their size and shape might become uncontrollable, which restricts performance. A potential option is a capacitive coupling element (CCE), which can be used at a wide band, requires a smaller area, and typically has a simple structure [14].

Modern networks and handheld devices ensure that mobility of people is not an obstacle for communicating with others anymore. Smartphones have become the main communication tools due to their rather compact size, light weight, and mechanical robustness. For improved strength and also better aesthetics, phone manufacturers have started to use metal covers and side frames [15]. Metal covers and rims as conductive materials increase the size of the device's connected metal parts, which operate as an RF-ground for the antennas, which limits the free space around the antennas. Close proximity of highly conductive materials also leads to narrower bandwidth and decreased efficiency [15]. Antennas radiate poorly when enclosed by metal covers, as the structure resembles a small Faraday cage. To resolve this problem, phone manufacturers have started to integrate antennas straight into the metallic structures. For example, Apple's iPhone 4 among the first released metal-rimmed phones, has its antennas integrated into the rim.

Only days after the release of iPhone 4, Apple received a lot of complaints about connectivity issues, and their first solution was to recommend a particular grip for the users of the device [16], [17]. This solution clearly is not sustainable in the long run, and antenna designers are required to come up with new ideas for the future handsets. After iPhone 4, many other companies have released their metal-rimmed, or even metal-covered phones. Typical antenna has still been integrated to the structure, and it is usually separated from the other structures with a slot. In case of metal-covered phones, some slots are typically included to the back cover to improve the antenna performance.

This thesis focuses on metal-covered phones. Moreover, the main purpose is to design antennas for mobile phone that has a slotless and continuous metal plate as the back cover. The thesis is part of a research project with AAC Technologies [18], and the specifications for the antennas are defined by the project. The detailed requirements for the antennas are specified in Section 4. Briefly, the cellular antennas should be efficient, support MIMO and cover a wide range of frequencies. Additionally, the phone should have antennas for Wi-Fi (trademark for Wireless Local Area Networks (WLAN)), and Global Positioning System (GPS). In addition, this thesis studies the effect of the metal cover on the performance of antennas.

The structure of this thesis is as follows. In Section 2, the required background knowledge is explained by introducing the characteristics of an antenna, methods to evaluate its performance, and presenting examples of different antenna structures. Section 3 reviews the latest studies on antenna structures for metal-covered handsets. The theoretical part is followed by Sections 4–6, which present the main contribution by the author by explaining the research methods, presenting, and finally analyzing the results from the antenna simulations, respectively. At last, the thesis is concluded in Section 7.

2 Mobile antennas

Mobile phones require antennas to communicate. This section introduces the general properties and characteristics of mobile antennas, including all necessary parameters and techniques used in the research of this thesis. Latter part of this section focuses on different antenna types that are used in mobile devices.

2.1 Antennas in general

An antenna is the single most important part of a radio system. The purpose of an antenna is to transmit and receive radio waves. Thus, it is designed to transform guided electromagnetic waves to free space waves, and vice versa (see Figure 1) [19]. As an electric signal travels from one point to another via a transmission line, e.g. a coaxial cable or a waveguide, the carried energy is bounded to the line or very nearby. Comparably, antennas work the other way: they are encouraging signals to propagate as far away from the antenna as possible, i.e. to radiate [20].

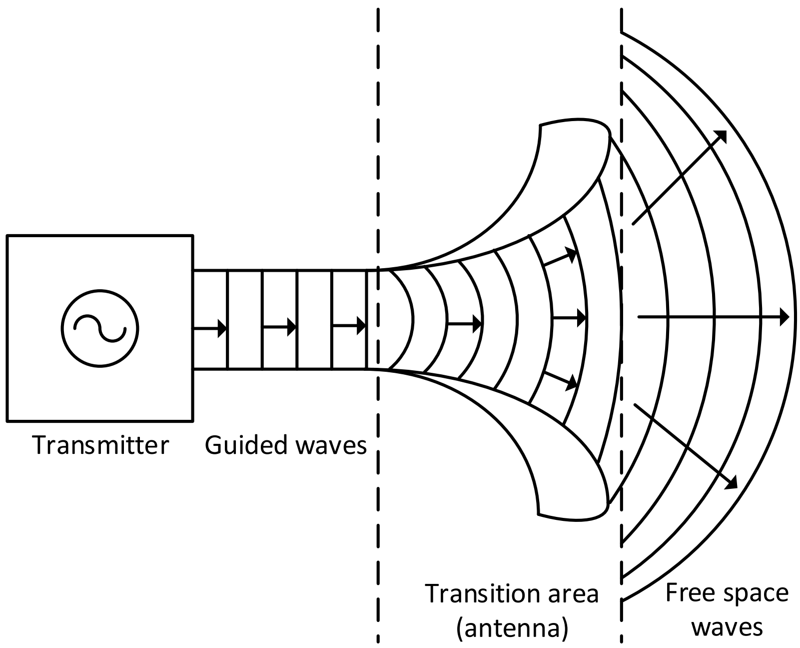
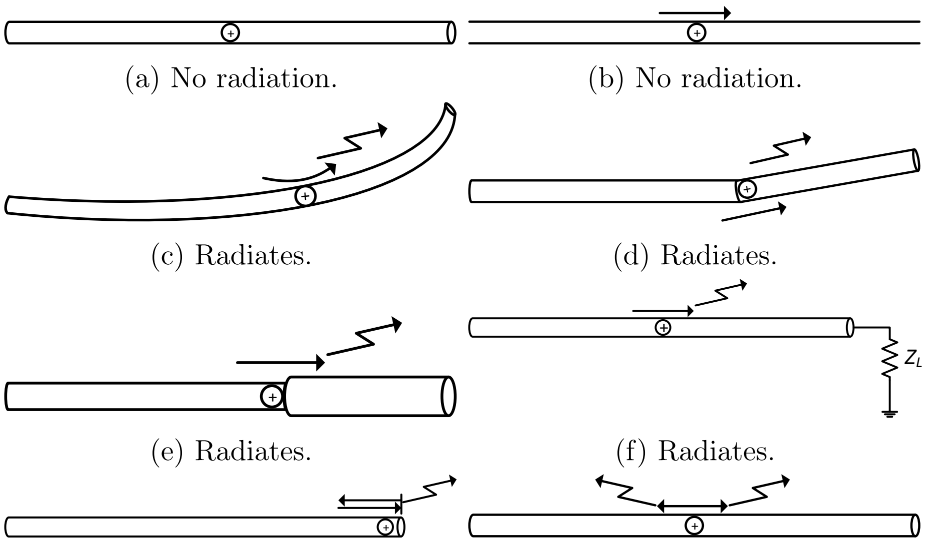


Figure 1: Principle of anan tenna operating in transmission presented in [12].

Antennas radiate because of accelerated charges [20]. Acceleration causes disturbance that initiates electromagnetic fields to propagate away from the source of the disturbance. The acceleration of charges occurs as change of speed or direction of the charge. As an example, a case of a single thin wire and a single charge can be considered. Figure 2 illustrates the following situations [12], [21]:

1. A stationary charge will not create radiation, since there is no current (2a).
2. A charge moving with constant speed will not create radiation, if the wire is straight and infinitely long (2b).

3. A charge moving with constant speed creates radiation, if the wire is either curved (2c), bent (2d), discontinuous (2e), terminated (2f), or truncated (2g).
4. A charge oscillating in a periodic motion creates radiation (2h).



(a) No radiation. (b) No radiation.
(c) Radiates. (d) Radiates.
(e) Radiates. (f) Radiates.
(g) Radiates. (h) Radiates.

Figure 2: Examples of charges producing radiation. Re-illustration from [12], [21].

The described situations are the most elementary examples of radiation. In the real world, the normal case is a steady-state charge oscillating, usually sinusoidally, and the oscillation frequency equals to the radiation frequency [20]. Once accelerated charges have started a wave, they are not needed anymore. Wave can sustain itself by closing electric field lines on themselves, since there are no charges present.

Maxwell has discovered that fields surrounding a transmission line are guided by the line itself [20]. In an open-ended transmission line, a standing wave is formed by the interaction between the incident wave and reflections. The standing wave has zero current at the end of the line and nulls every half wave length from there. The currents flowing in the transmission line wires are headed to opposite directions, which creates a strong, constructive interference of electric and magnetic fields between the wires. Bending quarter-wave long parts from the ends of both wires outwards exposes the reinforced fields to open space. In the formed half-wavelength dipole antenna, the currents are flowing to the same direction, and the maximum of its current distribution lies in between the halves [20].

Radiated waves propagate away from the antenna, to all directions, although not uniformly as antennas do not have any guiding structures in contrast to transmission lines [20]. Antennas are preferred to transmission lines when either the operating frequency is high, or the distance between the transmitter and the receiver is large. Increment of either of those increases costs and signal losses of transmission lines, which often makes antennas and wireless transmission a preferable choice.

2.2 Requirements for mobile antennas

Mobile antennas are typical examples of small antennas. Small antennas can be defined a few different ways [22]. *Electrically small antennas (ESA)* are not necessarily small in size, but they are small compared to wavelength. An ESA can be surrounded with a sphere of radius $r \leq \frac{\lambda_0}{2\pi}$, where λ_0 is the free space wavelength at the operating frequency. An antenna can also be *physically small (PSA)* if its measured dimensions are small. PSAs do not have any exact definition, rather than a sensual view of smallness. For this thesis, the main focus is on electrically small antennas.

As it is mentioned previously in Section 2.1, antennas radiate on a certain frequency, which is called the resonance frequency (f_0). The wavelength λ_0 is related to the frequency via propagation speed [20], which in the free space is the speed of light c,

$$f_0 = \frac{c}{\lambda_0}. \tag{1}$$

At resonance, a standing wave is formed at the antenna [20]. Since the resonance frequency is the same as the radiation frequency, the size of an antenna is related to the wavelength. For an electrically small antenna, the physical size of it is only a fraction of wavelength. Small electrical size results in small input resistance and large capacitive (or inductive for some antenna types) input reactance [22]. The input impedance of an antenna at resonance is (almost) purely resistive, and outside that frequency the impedance is changing quickly and therefore being the main limiting factor for the usable bandwidth [19]. This characteristic makes wideband matching, and thus achieving wideband performance difficult for electrically small antennas.

The three important characteristics of an electrically small mobile antenna are size, efficiency, and bandwidth, which are all interconnected [19]. Wider bandwidth can be achieved with a larger antenna, which is not desirable in a modern mobile phone. Decreasing efficiency might increase bandwidth, but it would also decrease handset's battery life. Thus, improving one of these parameters is possible by worsening the others. The important challenge in small antenna design is to find a good trade-off between the three parameters for each application.

The antennas in handsets and other handheld devices operate in demanding environment. Orientation of the phone is rather random, especially in the standby mode. The signal between terminal and base station propagates in every way from line-of-sight to wide multipath arrival angles. The signal strength has to be adequate to counter fading from human head and hand. The hand-effect is a major problem for mobile antennas. Studies have shown that up to 70 % of the radiated power might get absorbed into user's hands [23]. Generally, the requirements for mobile antennas can be listed in the following way [12], [24]:

1. *Radiation pattern:* Due to the randomly changing orientation of the phone, an omnidirectional pattern in azimuth is desirable, as well as wide beamwidth vertically. Though, the precise pattern is not that important given the propagation environment and the proximity of the user.
2. *Input impedance:* Considering the number of used frequency bands today,

phones have wide operational bandwidths. The antenna should be well matched to the source at all required bands.

3. *Efficiency:* Since omnidirectional antennas have low gain, it is critical to have good efficiency in order to transform input power to radiation. Efficiency might be the most important figure-of-merit for mobile antennas.
4. *Size:* Mobile devices consist of many subsystems, and nowadays require multiple antennas. Together with the constrained physical size of the handset, the antennas should be as small as possible. However, small size creates challenges as other requirements cannot be neglected.
5. *Manufacturability:* Mobile phone antenna is useless if it is not robust against mechanical damages or cannot be mass produced with reasonable costs. Also, antennas should fit the appearance requirements of the consumer product.

The following Sections 2.3–2.6 discuss the first three of these requirements in more detail.

2.3 Antenna impedance and efficiency

An antenna can be modeled with an electrical equivalent circuit consisting of two resistances and one reactance (Figure 3) [12], [20], [21]. One of the resistances represents ohmic and other losses (R_o) and the other is radiation resistance, R_r. It models the power loss from the circuit due to radiation, i.e. radiated power. Antenna's input impedance [20], [21] is defined as

$$Z_a = R_a + \mathrm{j}X_a, \tag{2}$$

where antenna resistance $R_a = R_o + R_r$ and X_a is antenna reactance, which models the energy stored in the near-field of the antenna.

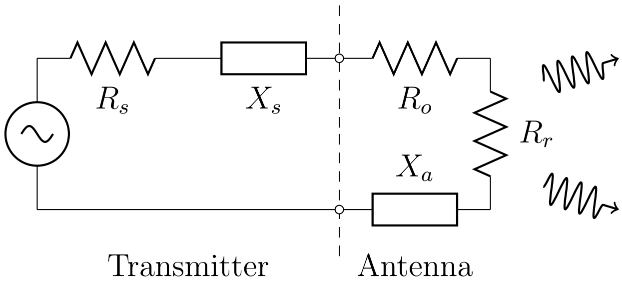


Figure 3: An equivalent circuit for a generator connected to an antenna. [12]

In the electrical equivalent circuit, the antenna is connected to a generator. Some of the input power P_{in} is dissipated in ohmic losses, and only a portion of it, P_{rad} is radiated. Radiation efficiency describes how much of the power is radiated, in other words utilized. The radiation efficiency [25] is given as

$$\eta_{\mathrm{rad}} = \frac{P_{\mathrm{rad}}}{P_{\mathrm{in}}} = \frac{R_r}{R_r + R_o}. \tag{3}$$

Efficiency can also be approximated with system's S-parameters. As radiated power is considered as power lost from the system, all S-parameters of an N-port system are required when determining the radiated power. For a lossless system, efficiency for port i [24] can be expressed as

$$\eta_{\mathrm{rad}} = 1 - \sum_{j=1}^{N} |S_{ij}|^2, \tag{4}$$

where S_{ij} is the scattering parameter expressing the power flow from port j to port i. For other than lossless systems, this works only as an approximation due to e.g. substrate or ohmic losses [24].

Good efficiency may be the most important property for any antenna. An efficient antenna requires less power for transmitting a signal with desired field strength. Higher efficiency also improves antenna's Signal-to-Noise Ratio (SNR), which increases the signal quality in reception. Therefore, an efficient antenna can improve the link quality and battery life of handset [5]. In an ideal situation, $\eta_{\mathrm{rad}} = 1$. As mobile antennas operate on wide range of frequencies, this is impossible to realize, and the typical realized efficiency is in the range of 0.3–0.9 [26], [27].

2.4 Radiation characteristics

Radiation pattern shows the far-field radiation properties of an antenna [20], [21]. It tells the strength and phase of radiation in a certain direction with respect to an isotropic radiator radiating the same energy [21]. An isotropic radiator is physically unrealizable, but it is used as a reference of radiation characteristics due its definition: lossless antenna radiating equally to all directions [21]. More realistic type is a directional antenna [21], which radiates significantly more energy in some direction than in others. Special type of this pattern is referred to as omnidirectional [21], which has a nondirectional pattern in a given plane (usually azimuth plane) and directional in an orthogonal plane (usually elevation plane).

Usually the pattern is expressed as a function of the directional coordinates: azimuth angle ϕ and elevation angle θ. Strengths of radiated electric or magnetic fields in the far-field are referred to field patterns, while the power density of them is power pattern. Often radiation patterns [20] are normalized to their maximum values

$$F(\theta, \phi) = \frac{E_\theta}{E_\theta(\max)}, \tag{5}$$

where E_θ is the θ-component of the electrical field and $E_\theta(\max)$ is its maximum value. For any radiating element, field patterns [20] can be expressed in a general form

$$F(\theta, \phi) = g(\theta, \phi) f(\theta, \phi), \tag{6}$$

where $g(\theta, \phi)$ and $f(\theta, \phi)$ are the element and pattern factors, respectively. Pattern factor is an integral over the current distribution in space and element factor is the pattern of an infinitesimal current in the distribution [20].

Generally, for a good communications link, it is useful to know how an antenna concentrates the radiated energy. Directivity describes this property. Normally, the word *directivity* refers to the maximum directivity ($D_{\max}$) of an antenna, but the parameter is actually dependent of the observation point. It is defined as the ratio of radiation intensity in a direction to the average intensity. Directivity [20] in a certain direction can be expressed with normalized power pattern

$$D(\theta, \phi) = D_{\max} |F(\theta, \phi)|^2. \tag{7}$$

Thus, directivity is a purely directional characteristic determined by the power pattern of an antenna. As antennas are parts of a radio system, besides their ability to focus radiation to certain direction, also their capabilities of transforming power at input terminals to radiation is practical to know. The feature combining all this information is called antenna's gain. Since all of the input power is not radiated, and especially electrically small antennas are very inefficient, gain might be more useful than directivity in case of mobile antennas. Gain [20] is defined as

$$G(\theta, \phi) = \eta_{\mathrm{rad}} D(\theta, \phi). \tag{8}$$

Mobile antennas typically have more or less omnidirectional pattern [28], due to the fact, that a user cannot know where the nearest base station is. Since omnidirectional pattern is nondirectional in one plane, antennas of that type usually have low gain which makes efficiency even more important parameter for mobile antennas.

2.5 Impedance matching

As the primary objective of an antenna is to convert waves bounded to transmission line to free space waves, the antenna has to be matched to the source in order to avoid reflections. Matching also improves SNR of the system and reduces amplitude and phase errors [25]. Reflections occur in the connection point of a transmission line and the antenna, and large reflections prevent maximizing radiated power in transmission or utilized power in receiving. Maximum power is obtained when the antenna is conjugate matched [20] to the source impedance $Z_s = R_s + \mathrm{j}X_s$ (or to load impedance, respectively)

$$Z_s^* = Z_a, \tag{9}$$

$$R_s - \mathrm{j}X_s = R_a + \mathrm{j}X_a. \tag{10}$$

For a perfectly matched antenna, the reflection coefficient is zero. Reflection coefficient Γ [20] is defined followingly

$$\Gamma = \frac{Z_a - Z_s^*}{Z_a + Z_s}. \tag{11}$$

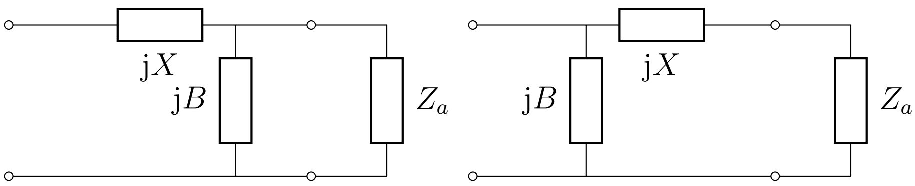
In an ideal situation, a perfect matching can be obtained at a single frequency. This is stated by Bode-Fano criterion for different load topologies. For a parallel RC-load, the criterion [25] is given as

$$\int_0^\infty \ln \frac{1}{|\Gamma(f)|} df \leq \frac{\pi}{RC}, \tag{12}$$

where $\Gamma(f)$ is the reflection coefficient as a function of frequency and R and C are the resistance and capacitance of the load, respectively. The criterion describes an upper limit of performance. Further analysis on this, which is out of the scope of this thesis, results in a few conclusions [25]:

- broader bandwidth can be achieved only if reflection coefficient increases.
- reflection coefficient can reach 0 only at discrete frequencies, i.e. having bandwidth of 0.
- circuits with higher quality factor (Q) are harder to match than low-Q circuits. Q depends on R and C (and/or L, depends on the load), and if either of them increases, the circuit's Q-factor increases, which complicates matching.

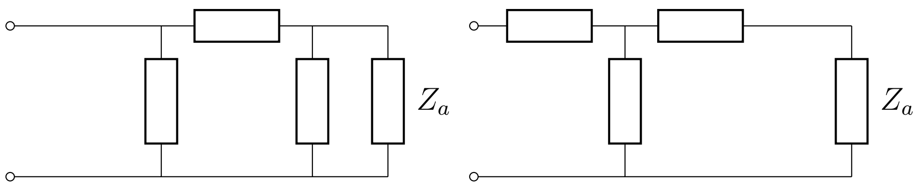
A good impedance matching can be achieved in several different ways, as presented in [25], and probably the simplest possible is an *L-section* matching circuit of two lumped elements. Figure 4 shows the two possible layouts for an L-section. In both configurations, the reactive elements can have any inductor-capacitor combination, in order to match the antenna. The exact matching circuit depends on the antenna's impedance. With low frequencies, up to about 2 GHz [19], or small circuit size, L-section matching is feasible. The limitations of L-section come in the way when frequency or circuit size increases.



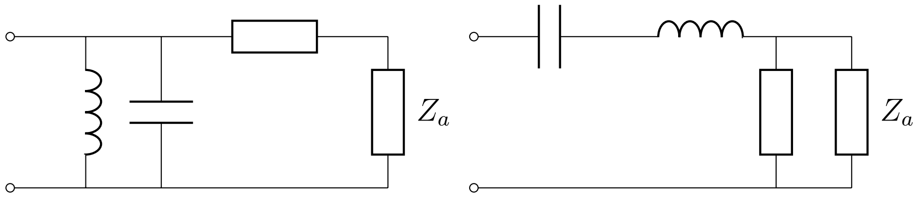
(a) Parallel susceptance first. (b) Series reactance first.

Figure 4: The two layouts for an L-section matching circuit [25]. Elements are either capacitors or inductors.

Usually applications, such as mobile antennas, require a wide band of frequencies. Although perfect wideband matching is impossible, antennas can be wideband matched to an adequate level, but it probably increases the complexity of the system [25]. Clearly, complexity isundesired, since simpler matching solutions are usually smaller, cheaper, and more reliable. In case of wideband matching, matching network might have to be adjustable in order to operate properly in the whole band. Figure 5 shows examples of different three elements topologies that are used with mobile antennas [29].



(a) Π-topology (b) T-topology.



(c) F-topology. (d) Γ-topology.

Figure 5: Four different matching networks consisting of three lumped elements. Blocks can be either capacitors or inductors [29].

Besides matching with reactive elements, also transmission line stubs can be used [25]. A stub can be either shorted or open-ended, and in parallel or in series with the feed line. One advantage of *single-stub tuning* is that it can be manufactured along with the transmission line media. Parallel stubs are useful with microstrip lines and series stubs with coplanar waveguides or slotlines.

While matching with a single stub, the matching level depends on the distance from the antenna and the length of the stub [25]. By choosing the length of the stub correctly, any reactance or susceptance can be obtained.

A major disadvantage with single-stub tuning is the distance between the antenna and the stub, especially when adjustable matching is desired. When matching is done for a single frequency, this should not be a problem. However, using a *double-stub tuner* might help with tunable matching solutions. It has two stubs at fixed locations, which makes the distance between the stubs and from the antenna constants. The first stub may even be connected directly to the antenna. Nevertheless, a double-stub tuner is not able to match all antenna impedances [25].

2.6 Bandwidth

Bandwidth expresses the operational frequency range of an antenna [21]. It can be described as a percentage from a center frequency (e.g. resonance frequency of a dipole) or a range from lower to upper limit (broadband antennas), where different parameters (e.g. gain, efficiency, matching) are still at acceptable level. Since antenna characteristics vary from not-at-all frequency dependent to critically affected by frequency, bandwidth cannot be clearly characterized. Usually it is specified separately for each application.

Bandwidth can be divided to pattern and impedance bandwidths [21]. Pattern bandwidth is associated with gain, side lobe level, and beamwidth while impedance bandwidth relates to input impedance, matching, and radiation efficiency.

Mobile terminals require a wide operational bandwidth, and small antennas are typically providing narrow bandwidth. As explained in the previous sections, there is a contradiction between bandwidth and matching level, which can be solved by finding a good trade-off between them. Bandwidth can be increased at the expense of antenna size or efficiency [19]. Multi-resonant matching circuits provide an efficient way to improve bandwidth. Adding resonators can double or triple the available bandwidth, but at the same time the complexity and losses of the whole system increase. Besides multiple resonators, wider bandwidth can be achieved with frequency tunable matching circuits. If the operational band can be split into sub-bands, that are not simultaneously needed, digitally tunable capacitors (DTC) can be used. As well as with multi-resonators, using DTCs also increase complexity and losses in the system. An example of a matching circuit with a DTC is used in [30], and shown in Figure 6. The third way to increase bandwidth is to sacrifice efficiency. Accepting worse matching level might nearly double the bandwidth [19], and efficiency would weaken mainly at the borders of the frequency band.

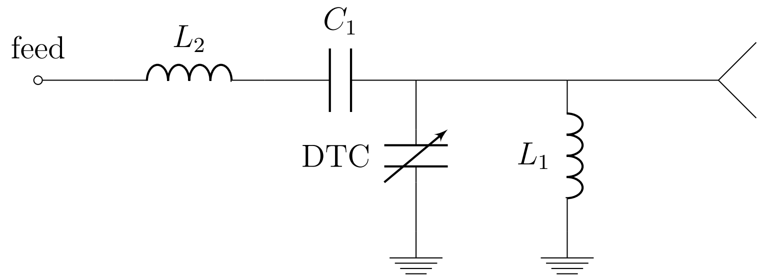


Figure 6: An example of a matching network of three lumped elements and a DTC presented in [30].

2.7 Typical antenna structures in mobile phones

An antenna can be any structure, which is able to convert guided waves to free space waves. Mobile antennas operate on a wide range of frequencies, and throughout the history of wireless communications, several different types of antennas are used for various purposes. Next, some of the most common antenna types in mobile, and other, devices are introduced.

2.7.1 Dipoles and monopoles

Probably the most fundamental antenna type is a dipole, which by the simplest is a transmission line with both its wires bent at one end [20]. A dipole is often used as an example of an antenna especially in educational purposes due to its simple structure. As dipoles are resonating antennas, their operational frequency depends on their length. The most widely used one is a half-wave dipole. By nature, dipoles are narrowband antennas, but wider bandwidth can be achieved by e.g. using larger wire width [20], [21]. However, even if dipoles are electrically small, they are usually physically large structures, which is not favorable for mobile and other handheld devices. Nevertheless, dipoles have also good features, like high efficiency and omnidirectional radiation pattern, which are wanted from mobile antennas. Well performing dipole structures for mobile phones are proposed e.g. in [31], [32].

Besides dipoles being physically too large for mobile applications, mobile antennas are surrounded by very nearby objects, that are harmful to the antenna. Normally, these objects are ground planes that are large compared to the antenna. Conductive ground planes affect antenna's performance, especially impedance and radiation pattern [20]. However, monopole antennas are designed to operate in the presence of a ground plane. A monopole is basically a dipole cut in half, and fed against the ground plane [20]. Monopole's impedance is a half of a dipole's, and accordingly, the radiated power is also a half of a dipole's with the same current, as the radiation occurs only in one hemisphere. This yields lower average radiation intensity, which gives higher directivity. Operational frequency of a monopole naturally depends on the length of the antenna, similarly to dipoles, but their smaller size makes monopoles more suitable for mobile devices. In [33], [34] designs for wideband monopoles to be used in handsets are presented.

2.7.2 Microstrip antennas

Microstrip antennas (MSA) are an alternative to wire antennas. For example, dipoles can be printed as microstrip lines. Typical microstrip antenna has a printed patch on the top of a substrate with a ground plane below it [20]. MSAs have a very low profile, since substrate is thin, and the patch itself normally has a thickness of $0.05\lambda_0$ or less. One advantage of microstrip antennas is that they can be included in microwave integrated circuits, which decreases costs, and provides controlled-dimension construction. Patches can also be printed on flexible substrates, which enables better use of available space [20].

Microstrips radiate with a broad beam broadside to the patch, while the ground plane prevents the formation of back lobes. A drawbacks of patch antennas is their resonant nature, which leads to narrow bandwidth. Also after fabrication, antenna cannot be re-adjusted easily. Due to the narrowband nature of this antenna type, and possibly large size, it is not very popular antenna for cellular phones [20]. However, Global Positioning System (GPS) is a standard feature in new mobile phones and it operates on a narrow band, and thus, microstrips with large dielectric constant substrate to reduce size are used for that purpose [20]. Mobile antennas might anyway be constructed with microstrip techniques, and commonly the patch is shaped according to other antenna type, as is done in [35], [36]. This might result in feasible performance on a certain band.

2.7.3 Loops and slots

Especially in receiving mode, loop antennas are a popular substitute for monopoles due to their resilience against noise [21]. Loop antennas have a poor radiation resistance, which is the reason why they are not commonly used in transmission. Their radiation resistance can be improved by increasing the number of the turns, which of course also increases losses [20]. Radiation pattern of a loop antenna equals to that of a magnetic dipole's. Also, a loop antenna can be mounted at any position to the mobile phone. Radiation characteristics differ a little between different orientations. Different loop structures for mobile communications are proposed e.g. in [37]–[39].

Slot antennas are variants of loops. Usually an antenna of this type is a slot in a ground plane [20]. The electric field distribution of a slot is equal to a similar dipole's, and the field is directed along the normal of the slot elsewhere in its surface except the slot region itself [26]. Slots can be fed from a waveguide, which makes these antennas popular for vehicles moving at high speeds [40]. Typically slots operate on a narrow band, which makes them not so popular choice for mobile devices [20]. However, slot antennas for mobile terminals are presented in [41], [42] with a decent performance.

2.7.4 Planar antennas

Since the space for antennas is very limited in mobile phones, traditional dipoles or monopoles might be too large. However, monopoles can easily be modified to fit the size requirements, as [21], [43] present. Bending the antenna forms a structure called an inverted L antenna (ILA). Replacing wires with a strip changes the structure to a planar inverted L antenna (PILA), which results wider bandwidth. PILAs are, however, sensitive to changes in height (h) or length (l) of the antenna. Height lower than $0.1\lambda_0$ is considered critical since above that the antenna is rather top-loaded monopole than a PILA [43]. Also, antenna's matching improves if h/l-ratio is greater than 4/3 [43].

Good matching can be maintained by adding a parasitic grounding strip near the feed point to form a planar inverted F antenna (PIFA). An example is illustrated in Figure 7. Even though the overall dimensions required for good performance, especially at low frequencies, might seem quite large, PIFAs and PILAs are suitable for cellular phones due to their low-profile structure and large achievable bandwidth [21]. Planar antennas have been used widely in mobile phones since their release due to the large modifying possibilities of the structure [43]. Wideband planar structures are presented e.g. in [44]–[46].

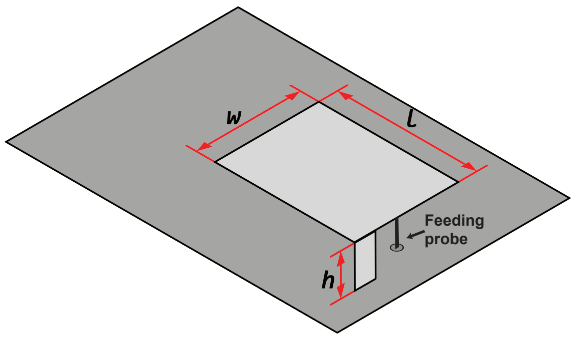


Figure 7: An illustration of a planar inverted F antenna.

2.7.5 Capacitive coupling elements

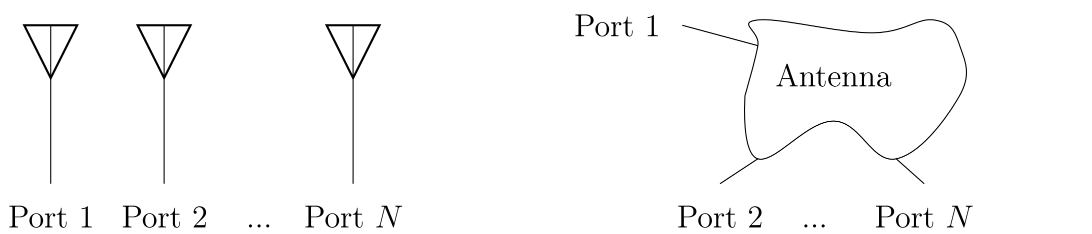
As all the previously presented antennas are of self-resonant type, capacitive coupling elements (CCE) are categorized as nonresonant antennas. Of course the element resonates at some frequency, but with suitable matching circuits the element is made to resonate at other than its nominal frequency [47]. Capacitive coupling elements were first introduced in [48] as a possible replacement for self-resonant antennas in mobile phones. A great advantage of CCEs is that the size of an antenna can be reduced significantly, considering that self-resonant antennas require rather large amount of space at low frequencies.

The concept of capacitive coupling elements is explained in [48], [49]. The basic idea behind them is to combine the wave modes of the antenna and the chassis. This results in an enhanced bandwidth for the mobile terminal. For a strong coupling to the dominating characteristic wave modes of the chassis, the maxima of electric fields of the antenna and the chassis must be close to each other. Moreover, the volume of the antenna should be used as efficiently as possible to maximize the field strength around the element. PIFAs for example, are not optimal structures for this purpose.

In contrary to self-resonant antennas, coupling elements are not the main radiators of the system, as [49] presents. The dominant wave mode of the chassis is much stronger than the same wave mode excited by the coupling element, which makes the ground plane the main radiator. With good matching circuitry, it is possible to excite multiple wave modes for a broad operational band [47].

2.8 Multiantenna systems

Mobile phones today have several radio systems for different applications, and the operating frequencies of them range from hundreds of megahertz to few gigahertz, in the future even to dozens of gigahertz [10]. The wide range of required frequencies usually demands for multiple antennas. Generally, these multiantenna systems are multiport systems, which can be distinguished in a few different ways [50]. The most intuitive one is a multielement antenna, in which each port is connected to a physically distinct antenna element (Figure 8a). If a single antenna element is fed from several ports, the different antennas can be separated by different polarizations or radiation patterns (Figure 8b). Additionally, a multiantenna system can also be a combination of these different types.



(a) Multiple separate antennas. (b) Single antenna with multiple ports.

Figure 8: Illustrations of multiantenna systems [50].

Multiantenna systems, especially multielement antennas operating at the same frequencies, are also known as multiple input, multiple output (MIMO) communications systems. They can enhance the capacity and bandwidth in wireless transmission [50], and exploit the spatial dimension of the channel, which has benefits such as robustness against fading and interference, and improve the signal power [51]. Use of multiple antennas enables transmission of several data streams simultaneously, even at the same frequency by combining diversity or beamforming techniques [26].

In a general communications link, the signal undergoes a multipath process, where the signal is reflected or scattered from various objects on the propagation path. Due to this effect, the electromagnetic waves are received from several directions, and this causes fading that lowers the signal strength [12], [26]. MIMO systems take advantage of this fading, as they collect energy from all the incoming streams, and sum them up. If the antennas are uncorrelated, the fading can be overcome [26].

Antenna diversity can indeed improve the performance of a communications system, if besides having good impedance matching, also the mutual coupling of the antennas is minimized. Isolation of the antennas is required for better efficiency, which improves the quality of the link [52]. Envelope correlation coefficient (ECC, ρ_e) expresses this information [53], [54]. ECC is the correlation between the envelopes of the signals for any two antennas of the multiantenna system [52], [54]. It is defined by and calculated from the field patterns of the antennas. Calculating ECC from the fields is a demanding task, and in [53] an equation to gather the information from the S-parameters has been derived

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1 - (|S_{11}|^2 + |S_{21}|^2))(1 - (|S_{22}|^2 + |S_{12}|^2))}. \tag{13}$$

This equation is valid for lossless systems, but it can be used as an approximation for lossy structures, similarly to (4). ECC is used to evaluate the MIMO capability of a multiantenna system, and a coefficient below 0.5 is considered as good performance [55], [56].

3 Metal-covered handsets

Previous section explains the physical principles of an antenna. This section focuses on the recent antenna research, and more specifically, in designed antennas for metal-covered mobile phones. Metal-covered handheld devices are already popular, but the popularity of phones having metallic structures is still increasing. In this section, the possible antenna types and design techniques as well as different styles of metal coverings are explained by introducing examples presented in recently published scientific articles.

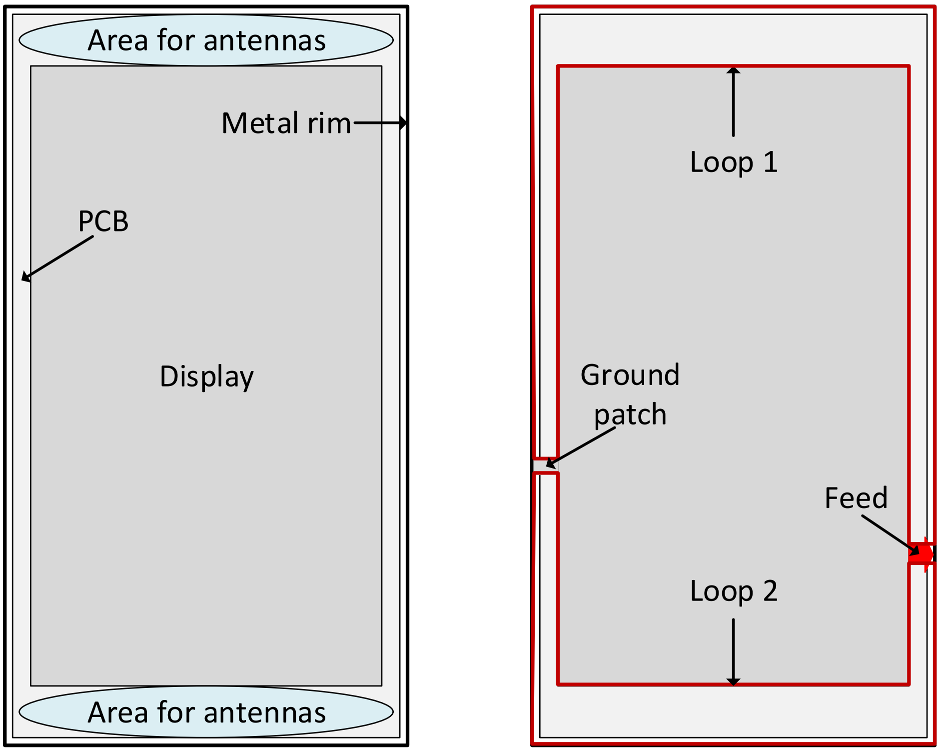
3.1 Antenna techniques in metal-covered handsets

Using metal rim on the sides of a handset improves the robustness and strength of the device, and also makes the appearance of the phone modern [57]–[59]. However, it affects the performance of antennas significantly. As the rim is made of metal, i.e. conductive material, it couples with the internal antennas and harms their radiation performance [57]. Presence of metal near the antenna weakens the impedance matching by adding a large capacitance to antenna's input impedance, and makes it difficult to obtain the same matching level again by adjusting antenna parameters. Since the matching level drops, also radiation efficiency and bandwidth decrease [57]–[59].

As smartphones have become more and more popular, another trend has been the increasing size of the touchscreen [60]. This alone complicates the positioning of antennas inside the phone, since the physical size of the phone should stay reasonable, but the display is wanted to be stretched as close to the edges of the phone as possible. Adding the metal rim is not making it any easier. Figure 9a shows the possible areas for antennas in a typical smartphone with a metal rim [58]. Areas on the printed circuit board (PCB) above and below the display are used for planar inverted F antennas (PIFA) or monopoles, with the display being the ground plane. Due to the negative effects of the metal rim on PIFAs and monopoles, slot and loop antennas integrated to the metal rim are an attractive choice [57], [58].

As the display is acting as an RF-ground, the metal rim can be grounded with a small patch [57], [61]. Placing a feed to another patch forms two loops between the display and the metal rim, as Figure 9b illustrates. This technique allows to keep the metal rim unbroken to maximize the strength of the phone. The length of the loop can be chosen such that different wave modes are excited. Since one feed-ground patch pair creates two loops of different lengths, both having own excited loop modes, this design can cover multiple frequency bands. Loops can also be located above the display, like traditional PIFAs [62], [63].

Different resonant modes can be obtained also with slots in the ground plane [59]. Combining slots with loops a large number of resonance modes can be achieved [58]. Each element supports several modes that can be excited simultaneously to obtain wide bandwidth. However, slots and loops require quite large space, which is already limited. Monopole antenna in the side metal itself saves space inside the phone for other applications [64], [65]. Cutting gaps to the metal rim constructs a monopole



(a) Typical locations of antennas in metal-rimmed handsets presented in [60].

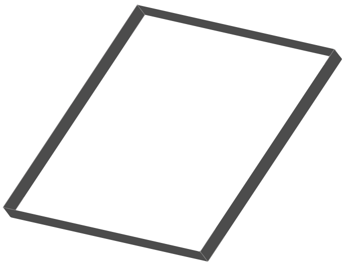
(b) An example of a dual-loop antenna in a metal-framed phone used in [57], [61].

Figure 9: Proposed configurations in previous studies.

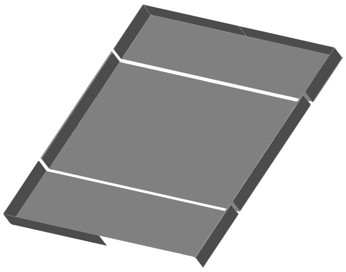
antenna, which couples with the rest of the rim to cover a wide set of frequencies [66]. Besides these antennas integrated into the structure, IFAs are also used [67].

From the metal rim on the sides of the phone, the next steps are a metallic back cover, and a full metal housing. Similarly to handsets with metal rim, metallic back cover improves robustness but deteriorates the performance of antennas. However, the harmful effects of full metal back cover are so strong, that many of the antenna solutions in the recent studies have slots in the cover (Figure 10). In those studies antennas are either PIFAs, or monopoles or the slots themselves [68]–[71].

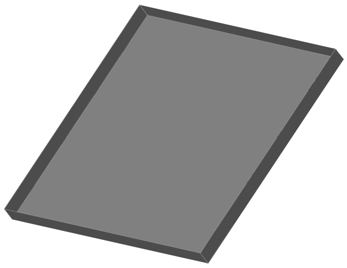
Few studies have still shown promising antenna designs for handsets with full metal back cover. These designs are based on PIFAs or L-shaped strips, but they require a part of the metal rim to be removed [68], [72]. These modifications make the handset not fully metal-covered, but as the metallic back cover is the main challenge in these cases, the proposed solutions are usable as they have achieved at least 40 % efficiency in the operating bands.



(a) Metal rim.



(b) Examples of slots.



(c) Full metal cover.

Figure 10: Re-illustrated examples of metal-covering a mobile phone presented in [72].

3.2 Key aspects in previous studies

More interesting matter in the previously studied antenna solutions is the technical details like operational frequencies and matching techniques. As can be expected of today's mobile devices, all solutions are for LTE networks. Still, only antennas proposed in [61], [65], [66], [69], [72] support LTE bands operating at 700–800 MHz. These solutions tend to have an average of 40 % efficiency in the low band.

As majority of the proposed solutions operate at frequencies 800–960 MHz and $1.7 - 2.7$ GHz, the performance of the antennas in these ranges is obviously better. Typical efficiencies for the low band are on average around $50 - 70$ % and for the high band 60–80 % [57], [66], [69], [71], [72]. The effect of user's hand or head is also measured in [57], [62], [63], [66], [67], [71]. The effect is significant since efficiencies drop to average of 10–30 % in all supported bands.

A common factor in nearly all of the referenced designs is that the antennas require almost the whole width of the device, which makes the antennas rather large. Only [68], [70] report clearly smaller antennas. Usually the total volume occupied by the antenna is rather small, but the occupied area might be problematic from a design point of view. Few designs have encountered this by integrating antennas into the metallic structures, like in [64], [66], [70], [71]. This saves space inside the phone for other subsystems, and enables possibly larger elements to cover also the lowest frequencies. Also [65] proposes an antenna structure, which can be integrated into the metal rim, but however, the reported prototype does not include any metal covers.

Handsets with metal covers and/or frames create a challenging operational environment for antennas. Besides the physical structure of an antenna, matching circuits have a major impact on the final performance. Typically matching is done with lumped elements, and a common amount of them is two or three for each antenna [61], [68], [71]. Matching circuits improve isolation between elements, which leads to better element efficiency, as well as efficiency of the whole system, since the operating frequencies of the other elements can be blocked by filtering. Even though wideband matching is desired, it might be hard to achieve with fixed matching network. As resonance tends to occur in narrow peaks, digitally tunable capacitors (DTC) are used in antennas presented in [70], [72] to obtain good matching level over the whole band. To improve matching even further, few designs use band-stop [64], [68] or band-pass [66] filters, or reactive loading [66], [72] to improve antenna's bandwidth.

The common feeding mechanism in different solutions is single-feed [64], [66], [67], [70], [72], neverminding the number of antenna elements. Designed slot or hybrid antennas have only one feeding point, and the signal couples from the fed element to the others [58], [59], [69], [71]. Also the dual-loop antennas presented in [57], [61], [63] are excited to their wave modes by a single feed.

Multiple feeds are used only in designs that have also other elements than slots or loops, or have the same antenna structure copied to the other end of the phone. Clearly, in those situations each element or structure is single-fed, but total number of feeds is plural [61], [62], [69]. In [65], the design has only one antenna, but it is fed from two locations. Both feeds have their own matching circuits, and one of them operates at the low band while the other at the high band. This method results great and wideband matching levels with at least 55 % total efficiency.

In LTE networks, one way to increase throughput is applying MIMO techniques in data transmission. However, MIMO operations are not that much studied for metal-covered phones. The first design, seen in [69], has two similar antenna structures in both ends of the phone consisting of complex monopole and planar inverted F antennas. This structure provides full MIMO capability for all operating frequencies, although antennas' efficiencies are only ca. 20 % at the lowest supported frequency of 746 MHz. The second MIMO solution proposed in [61] has a dual-loop antenna between the ground plane and the side metal frame, and a capacitive coupling element. Since the CCE antenna operates only on the high band (1710–2690 MHz), and does not cover the low band, the design does not have full MIMO capability. The best multiantenna performance is reported in [62]. This design has a loop antenna coupled with T-shaped monopole in both ends of the phone. Additionally, both antennas have a PIN diode for reconfiguring the operating bands. The efficiencies of each antenna in each state of the diode are above 45 % for all frequencies.

Many of the proposed antenna structures are located at one end of the handset [58], [59], [63]–[67], [72]. All of these designs can be modified to support MIMO by copying the antenna to the other end of the phone.

The radiation patterns of these proposed antennas are mostly omnidirectional [58], [62], [64], [68], [69], [71]. In some structures [57], [59], [63], [67], a common trend is that the pattern becomes more random when the operational frequency increases. An interesting issue is that the structures with the metal cover [68], [69], [71] preserve their patterns better than the ones with only a metal rim.

A summary of these observations is presented in Tables 1 and 2 for metal-rimmed and metal-covered phones, respectively.

Table 1: Comparison of previously studied antennas in metal-rimmed phones. * denotes the dimension is not available.

Ref.	**Type**	**Volume** [mm^3]	**Ground plane** [mm^2]	f [MHz]	η [%]	**Matching network**	**Notes**
[57]	Dual-loop	$10 \times 70 \times 0.8$, $5 \times 70 \times 0.8$	115×70	824–960, 1710–2690	60–80	N/A	Unbroken rim
[58]	U-shaped loop + T-shaped slot	$8 \times 64 \times 0.6$	125×63	791–960, 1710–2690, 3410–3800	50–90	N/A	Unbroken rim
[59]	Slot	$15.5 \times 56.5 \times *$	115×56.5	824–960, 1710–2170	60–80	N/A	Unbroken rim
[61]	Dual-loop + CCE	$10 \times 70 \times 0.8$, $10 \times 70 \times 0.8$, $6 \times 12 \times 0.8$	110×70	698–960, 1710–2690	50–490	Π-topology for both antennas	Unbroken rim. MIMO capable.
[62]	Loop + monopole	$5 \times 70 \times 0.8$	125×70	824–960, 1710–2690	40–70	N/A	Unbroken rim. MIMO capable. Reconfigurable with PIN diode.
[63]	Coupled loops	$5 \times 45 \times 0.8$	110×60	824–960, 1710–2690	50–95	N/A	Rim with a slot
[64]	Monopole	$6.5 \times 50 \times 0.79$	132×74	824–960, 1710–2690	75–85	F-topology + four-component band-stop filter	Rim with slots. Antenna integrated to the rim.
[65]	CCE	$5 \times 50 \times 5$	100×50	698–960, 1710–2690	55–90	Four components for each feed	No rim in the phone, antenna is however integrable to it. Multiple feeds.
[66]	Monopole	$5 \times 70 \times 5$	130×70	698–960, 1710–2690	50–70	Four elements + two-component band-pass filter + one-component reactive loading	Rim with slots. Antenna integrated to the rim.
[67]	IFA	$8 \times 70 \times 0.8$	132×70	824–960, 1710–2690	55–80	N/A	Rim with slots

Table 2: Comparison of previously studied antennas in metal-covered phones. * denotes the dimension is not available.

Ref.	**Type**	**Volume** [mm^3]	**Ground plane** [mm^2]	f [MHz]	η [%]	**Matching network**	**Notes**
[68]	Coupled monopoles	$5 \times 20.5 \times 4$	120×65	1560–1690, 2410–2490, 4950–6510	average 40 or 70	Two-component band-stop filter	Full metal housing, with opening in the corner. Only for GPS and Wi-Fi.
[69]	Monopole + IFA hybrid	$16 \times 64 \times 0.8$, $16 \times 64 \times 0.8$	N/A	746–960, 1710–2170, 2300–2400	20–70	N/A	Metal back cover with slots. MIMO capable.
[70]	ILA	$8 \times 35 \times 5.2$	132×70	824–960, 1710–2170	30–55	Two elements + a DTC	Full metal cover with slots. Antenna integrated to the housing.
[71]	Slot	$1 \times 65 + 20 \times *$, $1 \times 65 \times *$, $1 \times 40 \times *$, $1 \times 48 \times *$	110×65	824–960, 1560–1690, 1710–2170, 2410–2490	40–65	Two elements	Full metal cover with slots. Antenna integrated to the housing.
[72]	Loop	$8 \times 64 \times 7$	116×64	700–960, 1710–2170	average 45 or 60	Three elements + two DTCs	Full metal housing with opening at the end of the phone

4 Design process and methods

After introducing the former results of metal-covered handsets, the focus moves now to the new results achieved in this thesis work. This section presents the targets of this thesis in more detail, as well as the methods for answering the research question and solving the defined problems. The last part of this section contains the results from the first, preliminary simulations to gather information for the actual antenna design process.

4.1 Design objectives and strategy

The objective of this thesis is to study feasible antenna structures for metal-covered mobile phones. The phone should have two similar cellular antennas (main and diversity) for MIMO operation. Additionally, two antennas to operate on GPS and Wi-Fi frequencies are to be designed. To clarify, from now on, the main antenna refers to the first cellular antenna to be designed, and the diversity antenna to the second one, regardless how their final performances will compare to each other. Table 3 below presents the goals and requirements for this project defined by AAC Technologies.

Table 3: The criteria for the antennas to be designed.

Parameter	**Value**
Reflection coefficient	$S_{11} < -5\,\mathrm{dB}$
Cellular efficiency	$\eta > 30\,\%$
Isolation between main and diversity antenna	$S_{21} < -15\,\mathrm{dB}$
GPS/Wi-Fi efficiency	$\eta > 40\,\%$
Frequencies	
Main cellular antenna	0.704–0.960 GHz, 1.71–2.69 GHz
Diversity cellular antenna	0.704–0.960 GHz, 1.71–2.69 GHz
GPS antenna	1.56–1.61 GHz
Wi-Fi antenna	2.4–2.484 GHz, 5.15–5.875 GHz

Electromagnetic (EM) simulations are made in CST Microwave Studio [73] (later CST). It is used to create antenna and phone models, and to calculate system's S-parameters. Simulations are focused on antenna's initial matching, i.e. S_{ii} for each antenna. The procedure of testing different antenna structures is straightforward: first a model is built, then simulated, and finally the obtained results are analyzed. Analysis focuses on the resonance frequencies, bandwidths, and matching levels. If the combination of these three parameters looks promising (e.g. sufficient levels and a rather wide band), a matching circuit is constructed to enhance the performance. Based on the previous findings, the model is modified aiming to wideband impedance matching, and then simulated again. The first tests are done with a simple model and a simple antenna design. While the antenna structures are getting better, the model of the phone is also modified to be more realistic.

The antennas are designed in order of significance. The cellular antennas are considered more important as they operate on the lowest frequencies, and therefore require the largest space. Thus, they are studied first. The development process of the antennas begins with the main antenna, and when it is operating properly, the same process will be applied to design the diversity antenna. The final step is to find solutions for GPS and Wi-Fi. Figure 11 illustrates the proceeding order.

The basic research strategy is first to find a structure for the main antenna to operate on the low band (LB, 704–960 MHz). Lower band is designed first, since it is harder to reach the determined matching levels and efficiencies at lower frequencies. Results from the previous studies have shown weaker performance at that range. Also, the required antenna structures are larger, which makes them more critical to be prioritized due to the already limited space available. After a reasonable performance is achieved at that band, the model will be modified to support also the high band (HB, 1.71–2.69 GHz). Accordingly, the design of GPS/Wi-Fi antennas is started from the lowest frequency, i.e. GPS (1.56–1.61 GHz), after which, the Wi-Fi frequencies (2.4–2.484 GHz and 5.15–5.875 GHz) are implemented. The process flow of designing one antenna is visualized in Figure 12.

Before moving to the next antenna, the design constraints have to be checked. One antenna is iterated until the targets are reached (Figure 13). When the antenna under development is performing according to the requirements, or at least at a decent level, the design of another antenna can start.

Designing antennas is not limited only to antenna structures. In order to reach the goals presented above, matching circuits (MC) must be designed as well. Finding usable topologies is done simultaneously with the EM simulations. Optenni Lab [74] and NI AWR Design Environment [75] (later AWR) are used for this purpose. The S-parameter file obtained from the CST-simulations is given to and read by these programs. Optenni Lab searches for the best matching network according to given frequency band settings and amount of circuit elements. Resulted circuits are modified and fine-tuned in AWR, to reach the defined design objectives. Also, the ideal circuit elements are later replaced with models of actual components in AWR to obtain more realistic results.

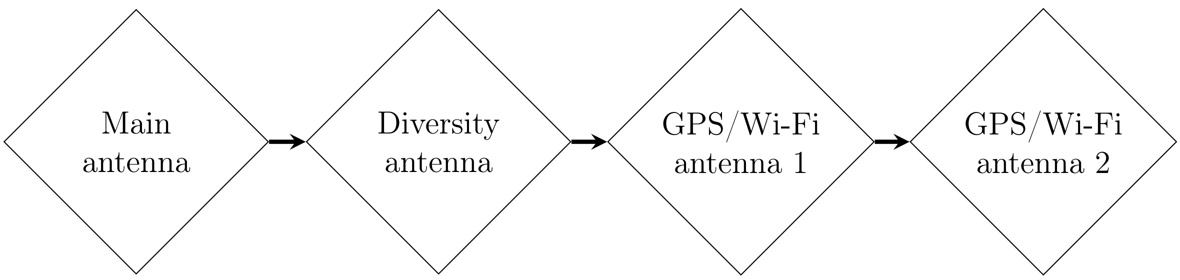


Figure 11: The design order of the required antennas.

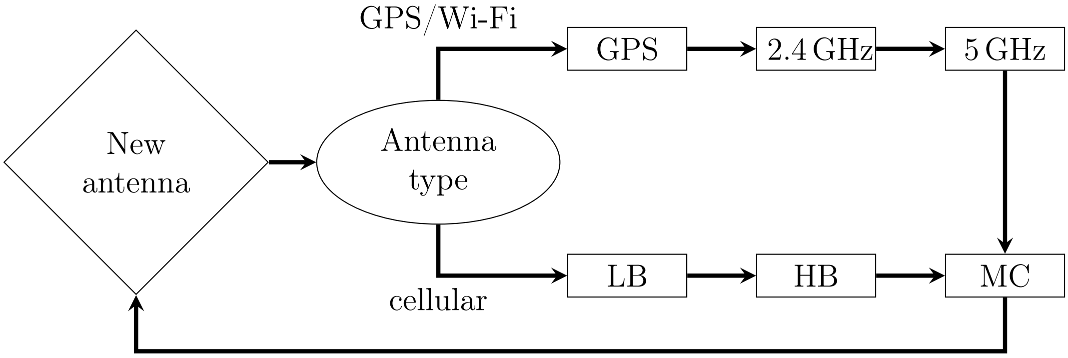


Figure 12: The design process of an antenna.

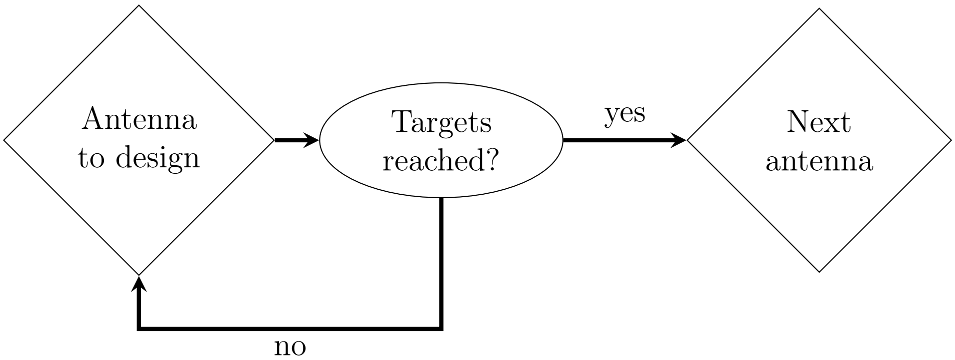


Figure 13: A single step of the whole process.

4.2 Electromagnetic model of the mobile phone

Besides the antennas, also the phone has to be modeled electromagnetically. For this project, it is specified to use a mechanically accurate model, shown in Figure 14, which is provided by AAC Technologies as well. However, this model is too detailed for research purposes, and thus it will be modified, which is explained more in Section 5.2. The model consists of a metallic back cover and side frame, plastic structure, and some subsystems of a phone. All parts except the plastic rim are modeled as perfect electric conductors (PEC) to reduce simulation times.

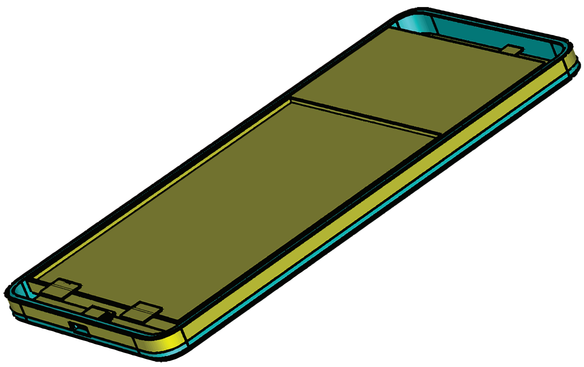


Figure 14: A 3D-model of a smartphone.

Before the precise model is taken into use, simulations are first done with a plain model. Basically, that is a PEC-sheet for the back cover, and an FR4-substrate with another PEC-sheet to model the display. Figure 15 illustrates the first phase model with the key dimensions of the phone marked into it. The antennas are built to the empty sides of the model, and eventually they would be integrated into the side frame of the accurate model. The simple model is used until a promising structure for the main antenna is found.

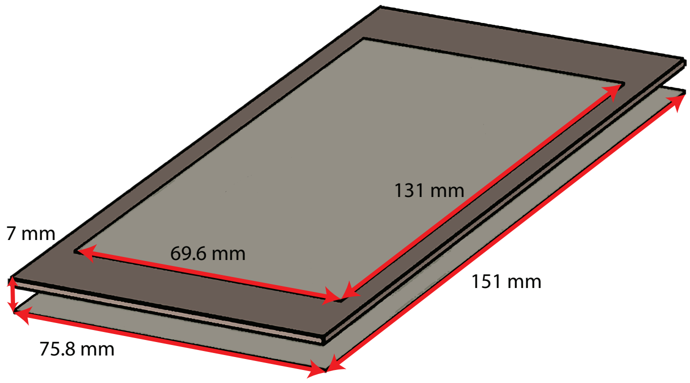


Figure 15: A simplified, basic model of a mobile phone to be used in the first phase of the simulations.

4.3 Preliminary antenna study

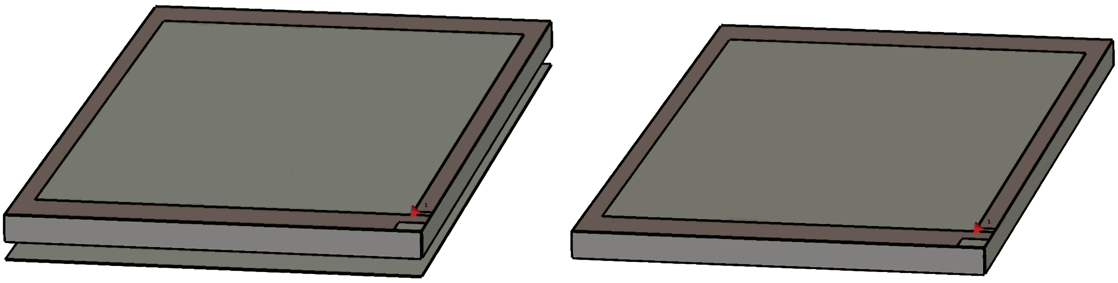
The first simulations with the plain model are about gathering knowledge on how different structures perform in the presence of the metal cover. Gaining this information is critical since antennas in metal-covered mobile phones are not that much studied, as is presented in Section 3.1. This preliminary study (later also pre-study) focuses on different dimensions of antennas, their locations, shapes, feed positions, and the metal cover itself. The structures of the antenna elements are kept as simple as possible in order to follow the effects of each parameter in an efficient way.

4.3.1 The effect of the metal cover

The main point of interest is the metal cover, and how it affects the antenna's performance. To demonstrate the challenge of this project, simulations to test the effect of the metal are run. Since this test is just an example, the simulation model is kept simple. A long, L-shaped antenna completely covering one long and one short side with a little square in the corner is used. Models are shown in Figure 16.

Figure 17a shows clearly the effect of the metal cover. At the low band, the results reveal a major difference. The aim of the matching level -5 dB is almost achieved when the metal cover is taken away without any external matching networks. With the metal cover the antenna resonates more with narrower peaks and has no desired matching level at any frequency.

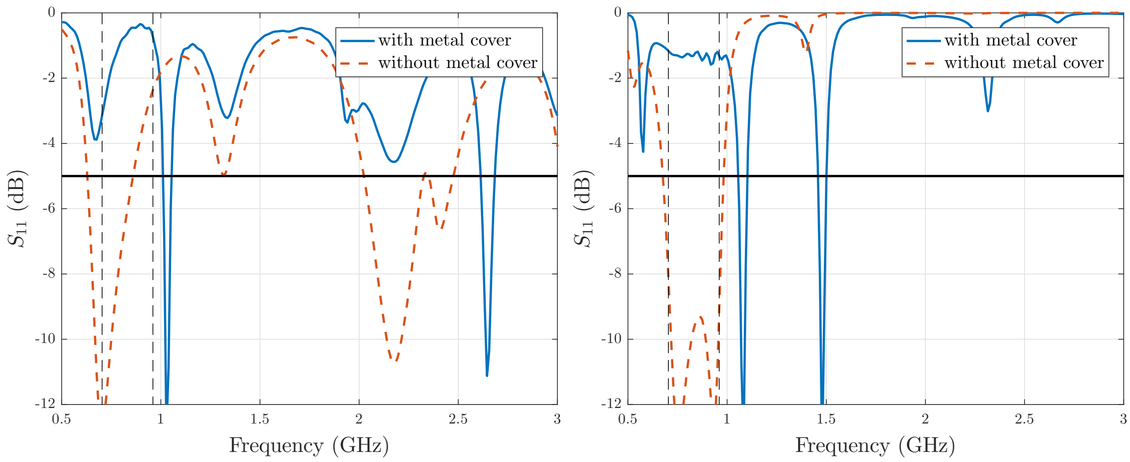
Figure 17b presents the same simulations with a four-element matching circuit designed with Optenni Lab. The software is set to generate matching circuits of four



(a) With metal cover. (b) Without metal cover.

Figure 16: The simulation models used to test the effect of the metal cover. An antenna element is on the side of the phone.

components, with −5 dB target efficiency. This time the difference is even larger. Without the metal cover the desired matching level is exceeded by far. In contrary, adding matching circuit to the other case is not much of help. Even though the level is now more constant in the band, it is far from acceptable, and the difference of these cases is about 8 dB.



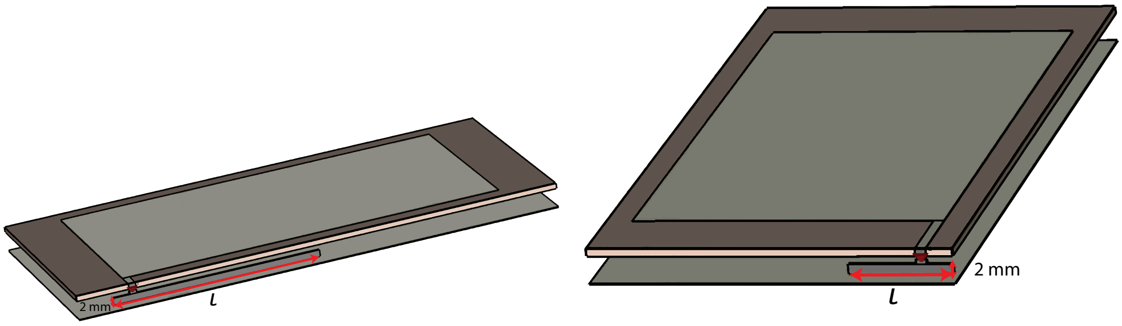
(a) Without matching circuit. (b) Matched antennas.

Figure 17: The effect of the metallic back cover on antenna performance.

4.3.2 Size of an antenna

As mentioned earlier in Section 4.1, the antennas are designed and developed in the EM simulator. Each simulated design provides information that is useful for the following iterations.

The first interesting metric to investigate is the size of the antenna. The length (l) and width (w) of the antenna are modified. The tested antennas are 2 mm wide metal strips either on the long or the short side of the phone (see Figures 18a and 18b, respectively). In both cases everything else is kept constant except the length of antenna.



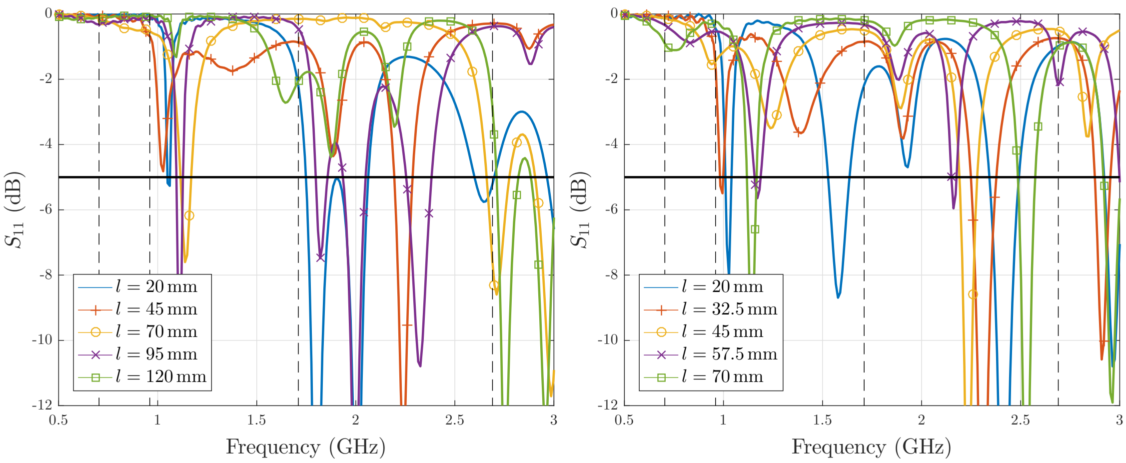
(a) An antenna located on the side of the phone.

(b) An antenna located at the end of the phone.

Figure 18: Models used to test the effect of antenna's length.

Figure 19 shows the effect of antenna length with five different values in both cases. Especially in the low band, none of these antennas is suitable. Anyhow, few observations can be made. Figure 19a reveals that the resonance of the longest antenna is the weakest and shorter antennas are better matched near the low band. Shortest tested antenna, having length of 20 mm, has the most promising performance in the high band.

The effect is quite similar, if the antenna is placed on the top end of the phone, like Figure 19b presents. Again, none of the tested lengths fits for the low band, but this time the length does not make as clear difference. Each of the tested lengths has strong resonances near the low band at slightly different frequencies. Comparing the two cases at the low band, it seems that antenna located at the end of the phone operates better, and larger elements are slightly better than smaller ones.



(a) Antenna located on the side of the phone. (b) Antenna located at the end of the phone.

Figure 19: The effect of antenna's length.

The other issue affecting the size of an antenna besides length is its width. The impact of width is tested with the same structure that is used to test the effect of length, when the antenna is placed at the end of the phone. Antenna's length is also 70 mm in this case. As Figure 20 presents, the effect of the width is quite minimal. Wider element gives a little bit better bandwidth in the both desired operational bands, but the difference is not significant. Despite the similarity of the results, larger bandwidth is more achievable with wider elements. Only it must be remembered, that the space for antennas is very limited on the sides of the phone, and thus, antennas cannot be much wider.

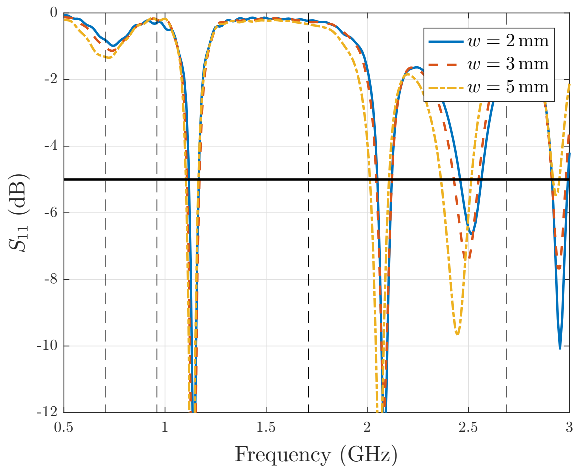
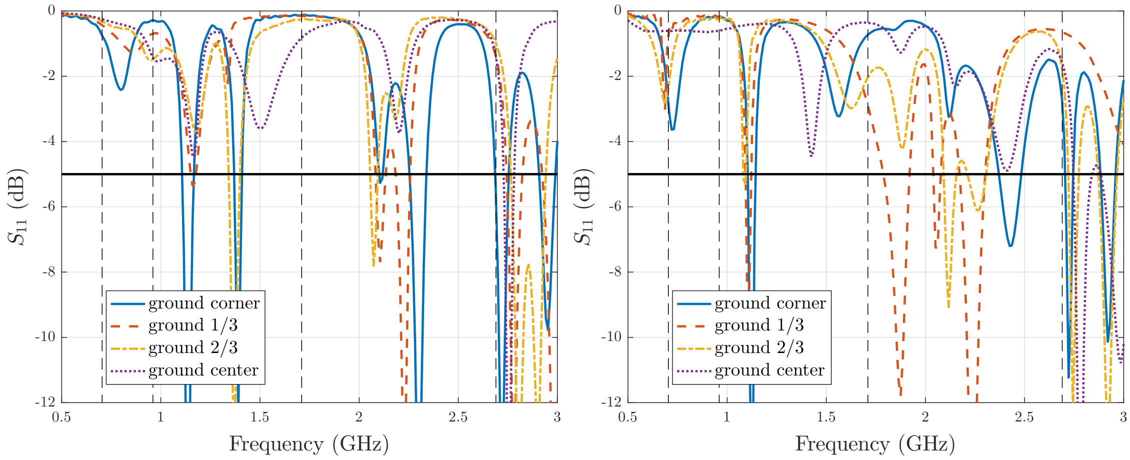


Figure 20: The effect of the width of an antenna.

4.3.3 Location of the feed

Besides the size of an antenna, another interesting parameter is the location of the feed. This is tested with the same structure that is used to test the impact of the metallic back cover except for the small block on the corner, shown in Figure 16a earlier. Feeds are located in two ways: either on the long or the short side, like in Figures 18a and 18b, respectively. The feed is placed between the antenna and the ground plane, i.e. the display, and four different locations are tested on each side. The first position is in the corner of the ground plane, and the last is at the center of it. Between these are two positions at equal distances, denoted as ground 1/3 and ground 2/3.

Figures 21a and 21b show the simulation results for the feed on the long side and at the end, respectively. Both of these graphs yield the same conclusion: in the low band, the most promising performance is achieved when the feed is located in the corner of the RF-ground. In the high band, the best location for the feed is near the corner on the top side of the phone.



(a) Antenna on the side of the phone. (b) Antenna at the end of the phone.

Figure 21: The effect of the location of the feed.

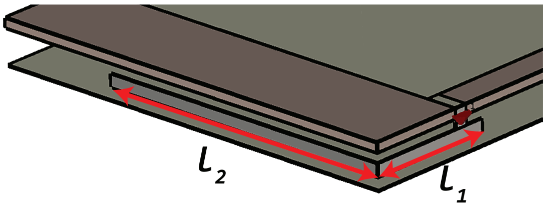
4.3.4 Position and shape of an antenna

Positioning of the antenna is worth testing as well. In this test, a 70 mm-long element is bent over a corner to form an L-shaped structure. The total length of this element is the same as is used earlier to have comparability. The antenna is positioned in one corner of the phone in four different ways presented in Table 4. The lengths on each side are kept the same, and positioning is changed by rotating the element. The feed is placed in the corner of the ground plane and is oriented along either the long or the short side. Figure 22a illustrates the model. In this illustration the feed is placed on the long side of the phone.

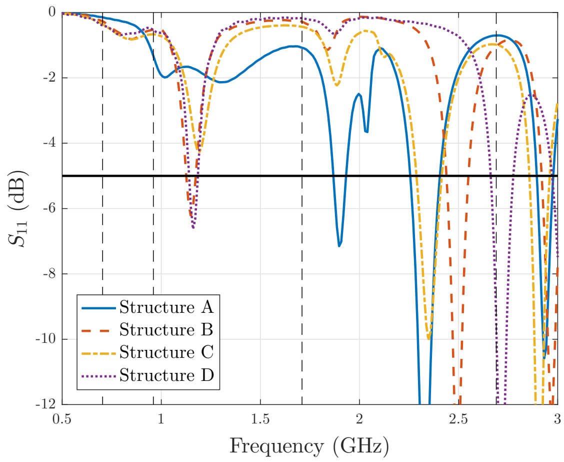
Results are presented in Figure 22b. The nature of each curve is very similar, especially other structures but A, that are almost identical below ca. 2.3 GHz. As these three structures have quite strong resonance above 1 GHz, the curve of Structure A is showing promising wideband performance. Although the good band is just above the low band, where performance of each setup is very weak, this test shows that wide band matching might be achievable with L-shaped elements in the corners.

Table 4: Antenna parameters used while testing L-shaped antenna structures.

Antenna structure	**Antenna length on the long side** (l_1)	**Antenna length on the short side** (l_2)	**Feed orientation**
Structure A	50 mm	20 mm	On the long side
Structure B	50 mm	20 mm	On the short side
Structure C	20 mm	50 mm	On the short side
Structure D	20 mm	50 mm	On the long side



(a) The model of an L-shaped antenna.

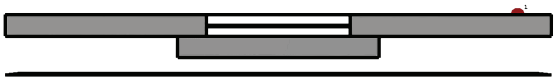


(b) Results from the simulations.

Figure 22: Simulated L-shaped antennas.

So far all investigated antennas have been either straight and rectangular, or L-shaped elements. Modifying the shape more might enable exciting different resonant modes. Figure 23 shows six shapes of different complexity implemented at the end of the handset. All the tested structures are fed from the same corner of the ground plane. To make it clear, the antennas of Shapes 4, 5, and 6 (Figures 23d–23f, respectively) are 0.5 mm apart from the cover.

(a) Shape 1.

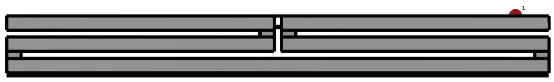


(b) Shape 2.

(c) Shape 3.

(d) Shape 4.

(e) Shape 5.



(f) Shape 6.

Figure 23: Different shapes for the antenna located at the end of the phone.

Results in Figure 24 show that for the low band, Shape 4 has the best matching and quite good bandwidth. The two most simple ones, Shapes 1 and 2, produce almost identical results, and in the lowest frequencies they are somewhat wideband, though the matching level is poor. These simpler structures also operate better in the high band than other tested antennas.

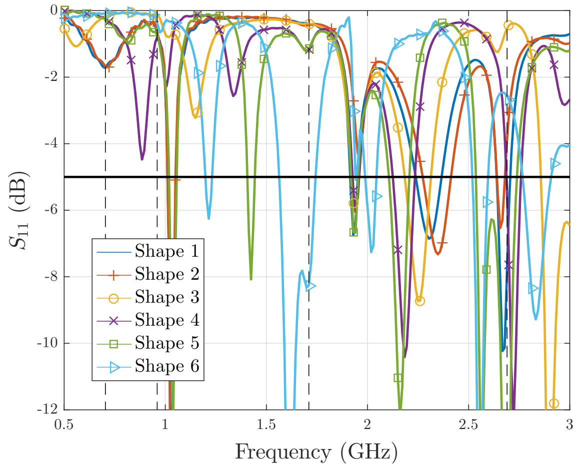
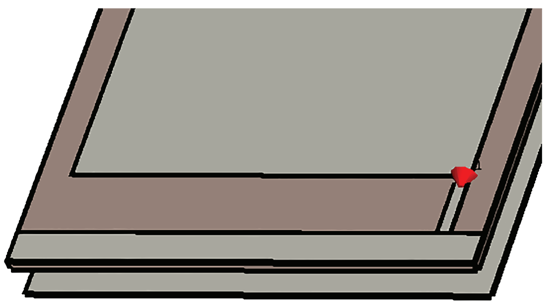
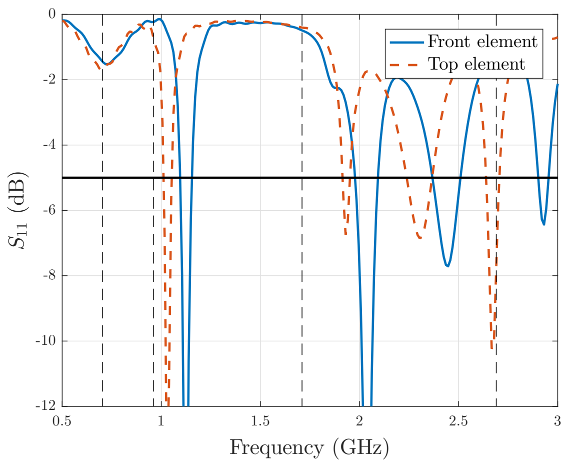


Figure 24: The effect of different antenna shapes. Antennas are located at the end of a phone.

As is shown in earlier Figure 9a, typical locations for antennas are the areas above and below the display of the phone. Therefore, an antenna element is placed in that area, as illustrated in Figure 25a, and compared to a similar element located at the end of the phone, like shown in Figure 23a. Figure 25b shows that the difference between these two locations is minimal. The shapes of the responses are nearly identical in the low band, and they follow the same pattern in the high band. Matching levels at the low band are bad and a little bit off the desired range, but the bandwidth is quite wide. In the high band, the element on the front gives good matching on two sub-bands, and is promising in the rest of the band as well.



(a) The model of a frontside antenna element.

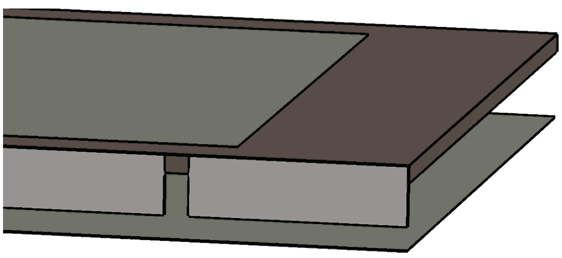


(b) Results from the simulations.

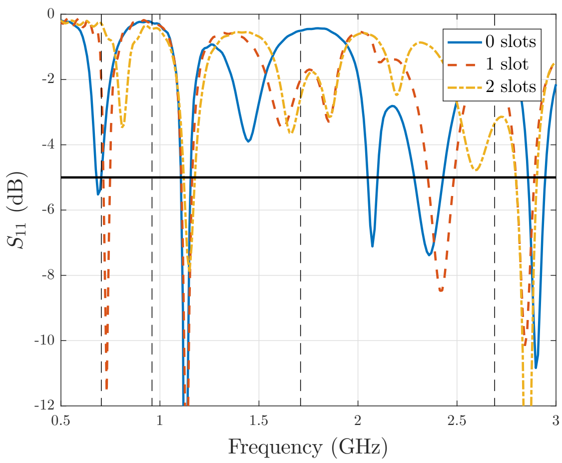
Figure 25: An antenna element on the front side of the phone.

In addition to straight elements, slots can be added to elements to introduce new wave modes. This test has the same antenna as presented in Figure 16a, with one or two slots on the sides. The first slot is on the long side, at 20 mm from the end, and the second is on the short side at the same distance from the end of the element. Both slots are 2 mm wide. The first added slot is shown in Figure 26a.

Adding one slot creates strong and very narrow resonance peak at the low band, as can be seen in Figure 26b. The second slot gives slightly wider bandwidth, but decreases the matching level compared to a case with zero or one slot.



(a) The model of a slot.



(b) The simulation results.

Figure 26: Slots included in the antenna element.

4.3.5 Ground plane

The last parameter to investigate in the pre-study is the effect of ground plane. So far phone's display has been used as an RF-ground, but since the back cover is also large metallic plate, that could be used for that purpose as well. The test setup is the same as is seen in Figure 16a. Only the feed is moved between the iterations. Figure 27 shows the impact. When the feed is moved to locate between the back cover and the antenna element, the response is slightly more resonating, but has wider bandwidths and generally better matching levels. One possible explanation for this behavior might rely on the sizes of the two planes. When the display is used as a ground plane, the larger back cover interacts more with the EM-fields and therefore is more harmful for the antennas. If the feed is grounded to the back cover, the disturbing element is then smaller and negative effects are not as strong.

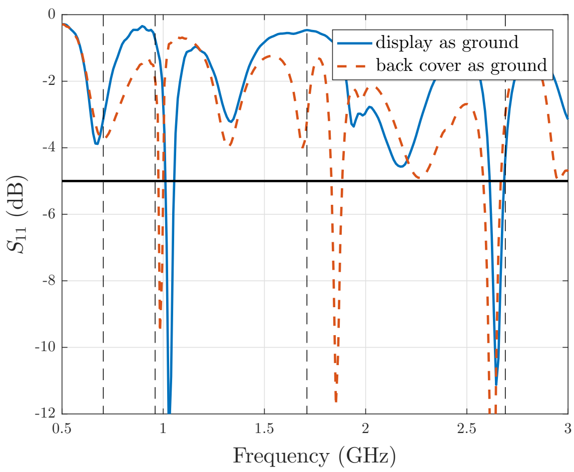


Figure 27: The effect of using display or back cover as an RF-ground.

4.3.6 Summary of the pre-study

The observations and conclusions made from all these presented simulation results are collected and summarized in Table 5 below. In this table, the effect of a matching circuit is not taken into account. Adding matching circuit affects the performance, and therefore might change the conclusions.

Table 5: Summary of how changing dimensions affect antenna's performance.

Changed parameter	**Impact at LB**	**Impact at HB**
Element length on the side of the phone	Resonances are outside the band.	Shorter elements operate better.
Element length at the end of the phone	Longer elements operate better.	Smaller elements operate slightly better.
Element on the front side of the phone	No major difference.	Matching levels are slightly improved.
Element width	Wider element slightly increases bandwidth.	Wider element slightly increases bandwidth.
Location of the feed	Feed close to a corner of the display gives wider band.	No major difference if the feed is on the long side. At the end, the bandwidth is wider if the feed is closer to the center of the ground.
Back cover as the ground plane	Improved matching levels	More resonance frequencies and better matching levels.
Shape of the element	Simpler is better.	L-shape resonates less than more complex shapes.
Slots	Slots create narrow resonances.	Matching levels decrease with slots.

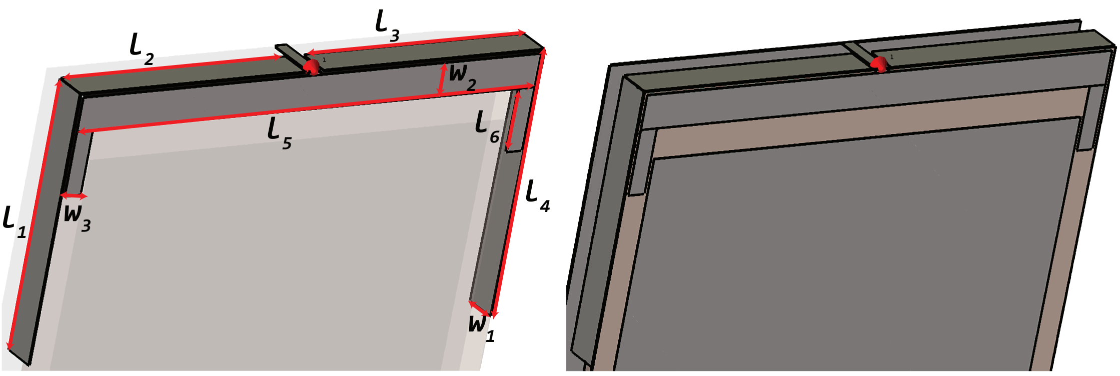
5 Antenna simulations

This section contains the majority of the work done for this thesis. The design problem is approached with two models of various complexity, and the antenna structure is developed in an organized way. Different subsections explain and present the results of different phases of the simulation process. Finally, all pieces are put together and the complete structure is formed.

5.1 Conceptualizing the main antenna

After the pre-studies, the actual concept for the main antenna is based on the design introduced in [76]. The findings from the pre-study also support the chosen approach. The main antenna should be located mainly on the short side of the phone and construct of simple shapes. Its elements should be rather short and they can be bended over the corner of the phone. Also, it is noticed that slots might improve bandwidth, and thus, they can be used to cover both defined frequency sets.

So, the main antenna is decided to consist of three elements. Two of them are L-shaped strips bending over the corners of the phone. The third element is a U-shaped sheet above the display on the frontside of the phone. Back cover is used as an RF-ground since it is earlier found to be better choice than the display. At first, this structure is single-fed, and the feed is connected between the U-shaped element and the ground plane. Figure 28a shows the structure of this concept, and Figure 28b gives a better view of the location of the antenna.



(a) Structure. (b) Location.

Figure 28: The concept for the main antenna.

The underlying idea of this structure is to have a strong mutual coupling between the three antenna elements, which would hopefully improve the operational bandwidth of the system. The elements are placed very close to each other to have better coupling effect. The gap between the U-shaped and the L-shaped elements is only 0.5 mm. The same gap width is also used between the barbs of the U-antenna and the display, and to separate the L-elements from the feed pin.

5.1.1 Initial concept

The concept is improved and modified further via a number of simulation rounds. Between the simulations, the structures and dimensions are modified the same way as it is done in the preliminary study. The main values of interest are highlighted in Figure 28a, and their initial values can be seen from Table 6. Besides these parameters, also the location of the feed and the different gaps between the elements are tested.

Table 6: The initial values for the main antenna concept.

Dimension	**Value** [mm]
l_1	40
l_2	36.5
l_3	36.5
l_4	40
l_5	75
l_6	9.5
w_1	5
w_2	5
w_3	2.55

Already the first simulation in Figure 29 shows very promising results. Shape of the response in the low band is exactly what is desired: wide and smooth. However, the results are not all positive. The matching level in the low band is only about -2 dB, and even worse in the high band. The first conclusion of this result is that either symmetric structure is not optimal, or the dimensions of the different parts are not what they are supposed to be.

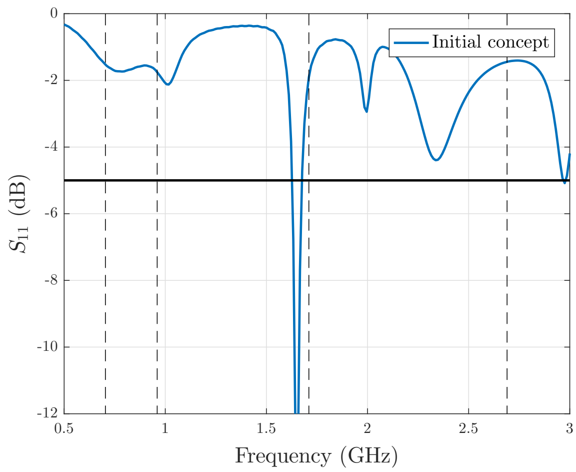


Figure 29: The simulation result for the initial concept.

5.1.2 Iteration of dimensions

The structure is first modified by changing the dimensional parameters. For now, the system is still kept symmetric to preserve simplicity. The changed dimensions are the lengths of the metal sheets beside the display (l_6), lengths of the antennas on the sides of the phone (l_1, l_4) and the width of all the side antennas (w_1). All these parameters are tested separately to follow the effects efficiently. As the observations are similar to the ones made in the preliminary study, only the best results are reported. Table 7 lists the best values for these parameters found in the three cases. Cases A, B, and C refer to changing l_6, l_1 and l_4, or w_1, respectively.

Table 7: Tested dimensions. All values are in millimeters.

Dimension	Initial	Case A	Case B	Case C
l_1	40	40	26	26
l_4	40	40	26	26
l_6	9.5	2.5	2.5	2.5
w_1	5	5	5	4

The values of the tested dimensions range from both larger than the initial value to smaller than that. Table 7 above shows that the best values are smaller than the initial one for all parameters. The results especially for l_1, l_4, and l_6 agree with the findings from the pre-study: better low band is achieved with smaller element on the side. w_1 however is smaller than the initial width but provides better results, even though the pre-study shows the opposite. In this case, as it is in the pre-study, the variations in the matching level between the different widths are marginal, but the chosen 4 mm provided the smoothest response in the low band.

Figure 30 shows the best results of the tested three cases compared with the initial situation. Each modification have improved system's performance in the low band. Although the focus is still in the low band, the high band should not be forgotten. In that range, the overall performance has not improved as the structure is modified.

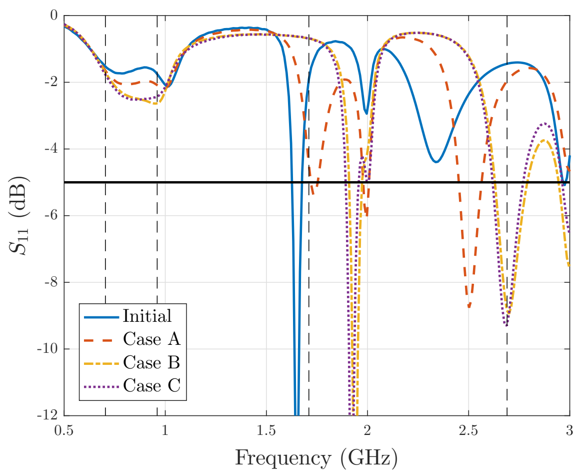


Figure 30: The best results from the three test cases.

Since the response of Case C in the low band is wide and below −2 dB, a matching circuit is generated for it with Optenni Lab. The program is set to generate a three-element circuit for either only low band or both bands aiming for the defined −5 dB matching level. Figure 31 presents the results. The desired matching level is reached in neither of the two settings. When only the low band is matched, a decent level of −4 dB on average is obtained. Adding the requirement for the high band does not create much difference to the situation without any matching circuits.

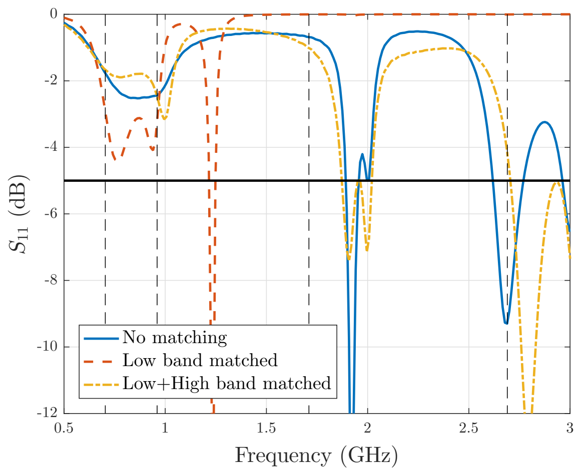


Figure 31: The simulation results of Case C with different matching circuits.

Since a suitable matching network could not be found for this structure, it means that the antennas should be modified more. One option would be to create two parallel matching circuits, one for the low band and the other for the high band. This however would increase the complexity of the system, which is undesired. Other possible solution could be modifying the antenna structures to be asymmetric, which is the preferable choice of the two options.

5.1.3 Asymmetric structures

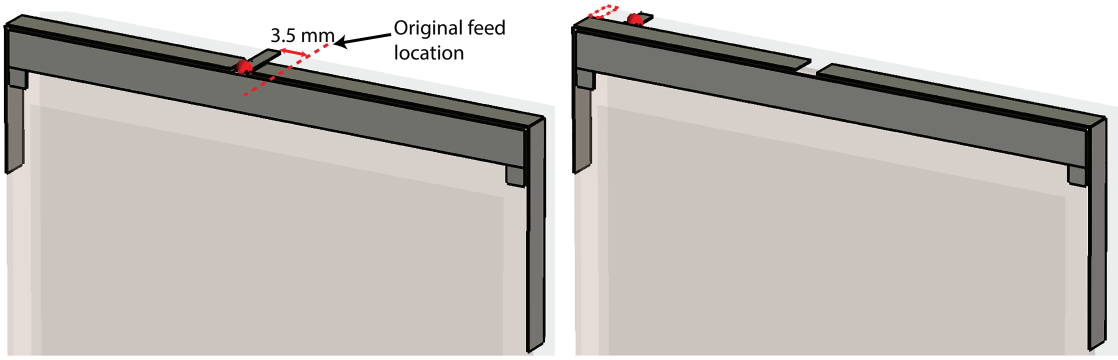
Asymmetric structures are tested with four different cases. Case D has an offset in the location of the feed, which causes the top-parts of the L-shaped elements to have different lengths. In Case E, the antenna parts on the sides of the phone are of different length. For Case F, the feed is transferred to the corner of an L-shaped element, and in Case G, the feed is offsetted from the previous location.

Again, only the best structures are presented of each case. Table 8 shows the changes in dimensions done in Cases D and E. In the best scenario of Case D the amount of offset is 3.5 mm to the left, and in Case G 5 mm to the right.

Table 8: Dimensional changes made to create asymmetry. All values are in millimeters.

Dimension	Case D	Case E
l_1	26	20
l_2	33	33
l_3	40	40
l_4	26	30

Figure 32 illustrates the structural changes of Cases D-G. The feed offset introduced in Case D is seen in Figure 32a. The red dashed line shows the original location of the feed, in the middle of the side frame. Also the changes in the lengths of the L-elements (Case E) can be seen. Figure 32b shows the feeding structure of Case G, and the red dashed area points out the feed position in Case F.



(a) The feed offset in the U-shaped element. (b) The feed placed in the L-shaped element.

Figure 32: The changes in antenna structure in Cases D-G.

Similarly to the cases with symmetric structures, the performance of the antenna system improves as the test cases proceed, like Figure 33 represents. Matching in the low band is still wide and levels have increased. Besides that, also the high band is showing major enhancements, especially in Cases F and G. Matching levels are fair over the whole band. The only drawback is that the response in the high band exhibits many narrow nearby resonances, which might be a problem when generating matching circuits.

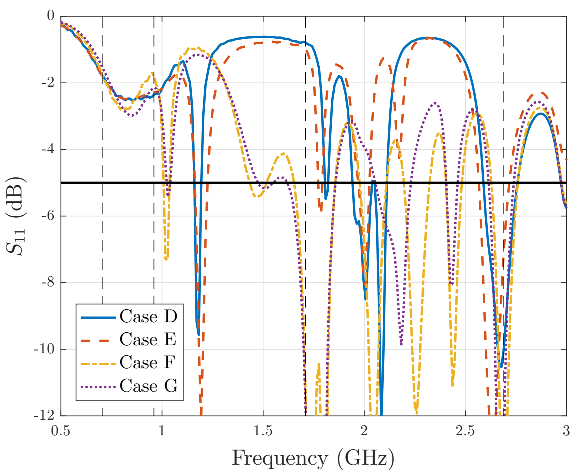


Figure 33: The best results from different asymmetric structures.

A matching network is generated also for the antenna of Case G. Optenni Lab is set to construct matching circuits for either low band, high band, or both bands with the target level of -5 dB. Each topology has three components. Responses can be seen from Figure 34. Surprisingly, the responses are more or less identical, even with the one without matching circuits. In the low band, a little more bandwidth is obtained when the antenna is matched, however, the matching level is still much worse than the target. In the high band, all topologies provide better matching, but the target level is not completely reached. One curious observation is that Optenni Lab resulted in the same topology for matching only low band or both bands. It can be concluded that the environment is very challenging for designing low band antennas, and moreover, matching them.

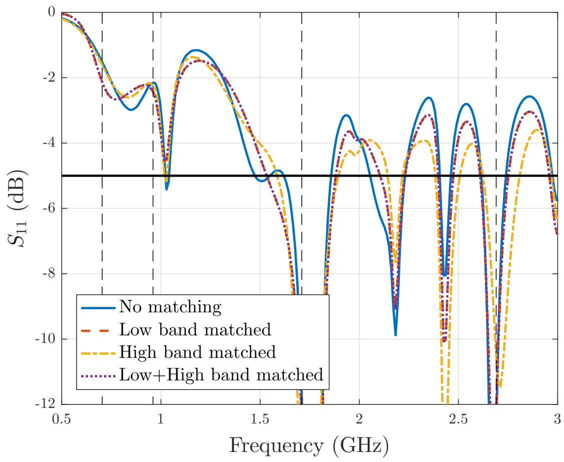


Figure 34: Impedance matching results for Case G with different matching topologies.

Accordingly, the antenna concept requires some asymmetry in the structure, and also is quite precise of its dimensions. Next, the element above the display is modified. Case H changes the gap between the U-shaped element and the top of the phone from 0.5 mm to 1 mm, which is seen as w_2 decreasing to 4.5 mm. The most radical modification is seen in Case I, where the barbs of the U-shaped element are removed, and only a straight metallic sheet is left (later referred as an I-shaped element). Figure 35 shows the updated structure.

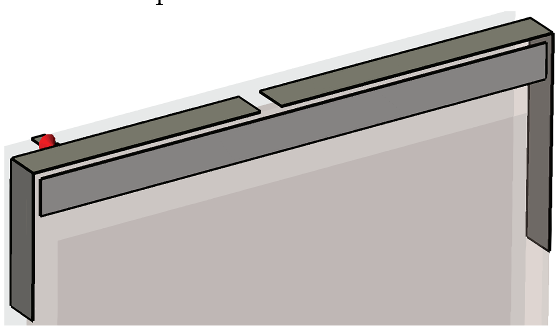


Figure 35: Antenna structure with a larger gap between the elements from Case H and I-element from Case I.

Figure 36 shows the best results of Cases H and I, compared to Case G of the previous round of tests. Transforming the U-element to an I-element is a good change. Even though the low band is a little off the required frequencies, achieved bandwidth is wider and smoother than in any test so far. Progress has also happened in the high band, where the response is not that peaky anymore. Instead, the overall shape is not as resonating as before, and matching levels are mainly better.

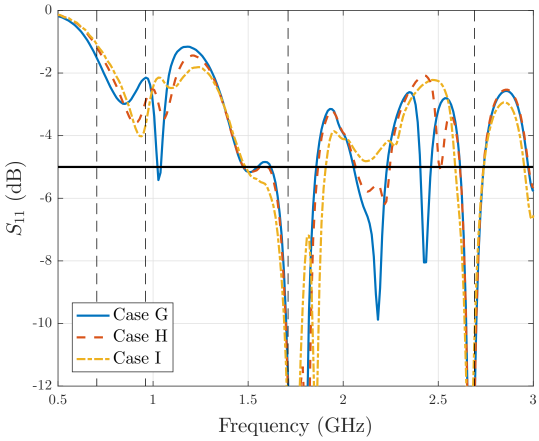
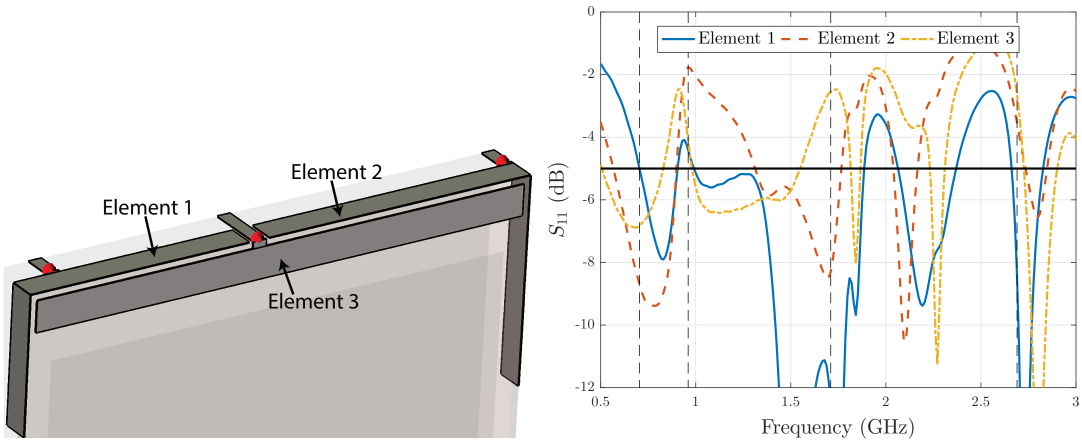


Figure 36: The simulation results from Cases H and I.

5.1.4 Antenna structure with multiple feeds

The conceptualizing phase is concluded by testing a structure with multiple feeds. So far, all structures in the pre-study and conceptualizing tests have had one only feeding port. As this currently studied structure consists of three separate but closely located elements, adding feeds to each of them is simple. This kind of system would result in a few advantages. First, the mutual coupling effect might be stronger and enable larger achievable bandwidth. Second, matching the elements may be simpler since each feeding port can be assigned with its own set of frequencies. However, this will increase the complexity of the whole system.

Figure 37a shows the modified structure for this test. Now the system has actually three antennas, named Element 1, 2, and 3, that are organized as marked in the figure. The results are presented in Figure 37b. The matching of the low band nearly reaches the requirements as only a small set of frequencies is uncovered. The performance of the high band is not as good, but still promising, and the levels of Element 1 are mainly adequate keeping in mind that the antennas do not have any matching circuits yet. Also, in a multiport system, the matching levels of each individual port are not as informative as with single ports. As power flows also between ports, the system might be very inefficient, and not radiate at all.



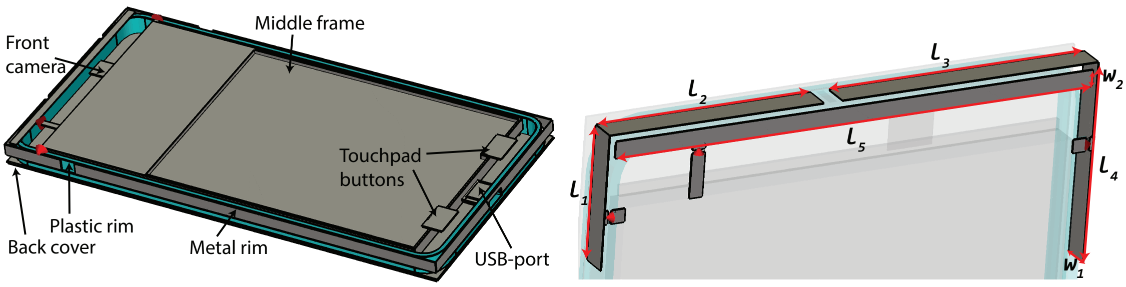
(a) Structure. (b) Results.

Figure 37: Antenna simulation with three feeds.

5.2 Simulations with the accurate phone model

As mentioned in Section 4.2, a mechanically very accurate 3D-model of a real smartphone is required to be used in the electromagnetic simulations. The model is, however, simplified a lot to keep the simulation times reasonable and modifying the antennas easier. Still, in addition to the metal cover, side frame, and antennas themselves, this model has a lot of other details like battery, USB-port, front camera, touchscreen buttons, and supportive structures like plastic rim or metallic middle frame. Otherwise the model is shaped like a simple box, except the plastic frame that is imported straight from the 3D-model. Rounded corners would have complicated creating and placing antenna elements to the model. Also, the difference in results is thought to be minimal.

The simplified model is presented in Figure 38a highlighting all the required details except the battery, which is underneath the middle frame. Figure 38b illustrates the dimensions of the antenna structure. The different parts are labeled equally to the conceptualizing phase to keep the two models comparable.



(a) The simplified model of a mobile phone. (b) Structural dimensions.

Figure 38: Illustrations of the realistic model and the main antenna structure.

Simulations with the accurate phone model begin by transferring the best structure from the plain model simulations to the realistic model. Besides the amount of details in the new model, the only differences are the widths of the antennas (w_1 and w_2) and the feeding structure. The value of w_1 is pretty much determined by the actual 3D-model of a phone and w_2 has to be thinner since wider antenna would block the front camera. Other dimensions stay the same as the values of Case E listed in Table 8 earlier.

Antennas are fed from the middle frame. As previous tests have shown, the back cover should be used as a ground plane, and therefore the middle frame is connected with grounding pins to the back cover. This choice would be more suitable for a consumer product, and a prototype could be built easier this way.

Figure 39 shows the effect of a more realistic environment on antennas. Comparing with Figure 37b, the matching levels for Elements 2 and 3 are a lot better, though this is mainly due to strong mutual coupling. The increased amount of metallic structures in the model causes the currents to distribute differently, which is seen as a different response than in Figure 37b. Anyway, this proves the antenna concept to be usable for this project.

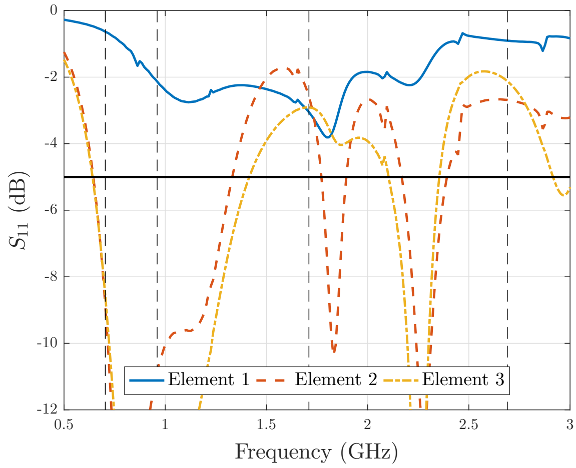


Figure 39: The original matching levels of the concept antenna in realistic environment.

5.2.1 Main antenna

The antenna structure is tested the same way as is the plain model. As the structure is discovered to perform well in both the low and the high band, a complete reconstruction is not needed. Only dimensions of the antenna elements and positions of the feeds are optimized. The final structure is shown in Figure 40 and the dimensions of each element are listed in Table 9. Now, the L-shaped antennas are integrated into the metal rim on the side. The rim is not unbroken, and the gaps are 4.43 mm on the sides and 2 mm on the top. Clearance between the I-antenna and the L-antennas is 0.6 mm at the end of the phone and 1.5 mm in the sides.

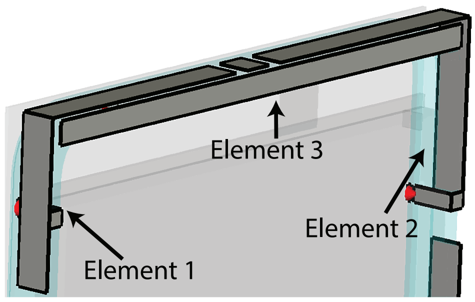


Figure 40: The final structures of the main antenna.

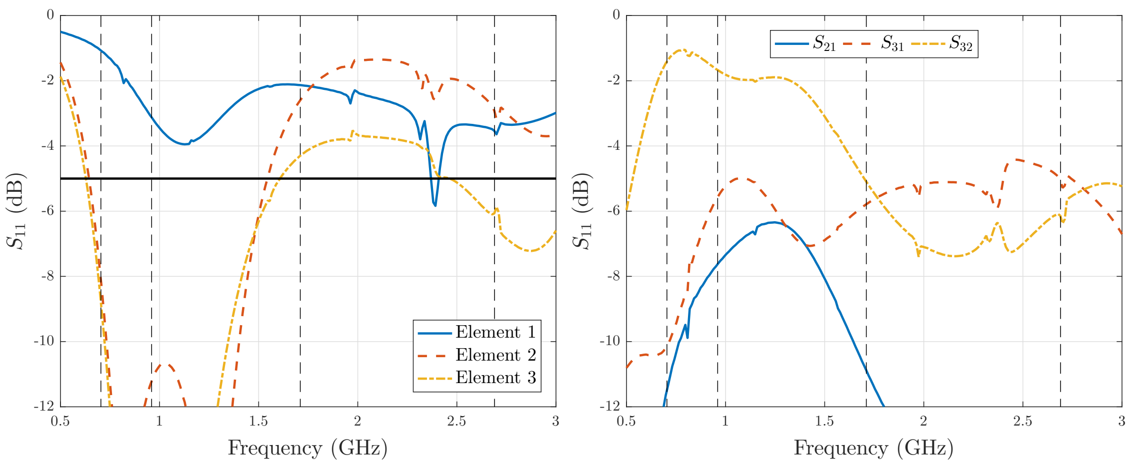
Table 9: The dimensions of the final antenna structure.

Dimension	**Value** [mm]
l_1	20.76
l_2	33
l_3	34.85
l_4	23.23
l_5	72.8
w_1	4.35
w_2	2.9

More significant changes are made in the feeds. Besides adjusting their positions, they are after all moved to be connected to the back cover instead of the middle frame. Even though the middle frame is grounded from several locations, connecting the feeds to the back cover gives larger bandwidth. However, this feeding structure is considerably more difficult to realize due to the limited space. The feeding pin is connected to the cover in the narrow area between the middle frame and the plastic rim, which does not leave much room for matching components or feeding cables in the real design.

At this point also matching networks will gain more focus. Based on the plain model simulations, the desired matching level of −5 dB or efficiency of 30 % for the whole operating bands will not be reached without external matching circuits, and that finding a good matching network is not an easy task.

As mentioned earlier, the purpose of having three elements close to each other is to have strong coupling between them to achieve wider operational band. However, this coupling effect also complicates matching the antennas. In many cases, the reflection coefficients of each element are very similar with at least one of the other elements. Figure 41a shows the similarity of Elements 2 and 3. A huge band is obtained with substantial matching level by either of the elements. The mutual coupling between the antenna elements is shown in Figure 41b. The figure presents the S_{ij}-parameters of the antenna system, where indexes i and j refer to the respective antenna elements. The mutual coupling is strong between Elements 2 and 3 in the low band, and this causes the elements to behave the same way while adding matching circuits. In other words, even if the matching level was suitable, nothing would radiate since all the power flows to the other ports. Due to this harmful effect the structure is modified throughout the simulations to have asymmetry between the elements and their behavior, but the differences are not significant, and therefore the problem has to be solved with good matching circuits.

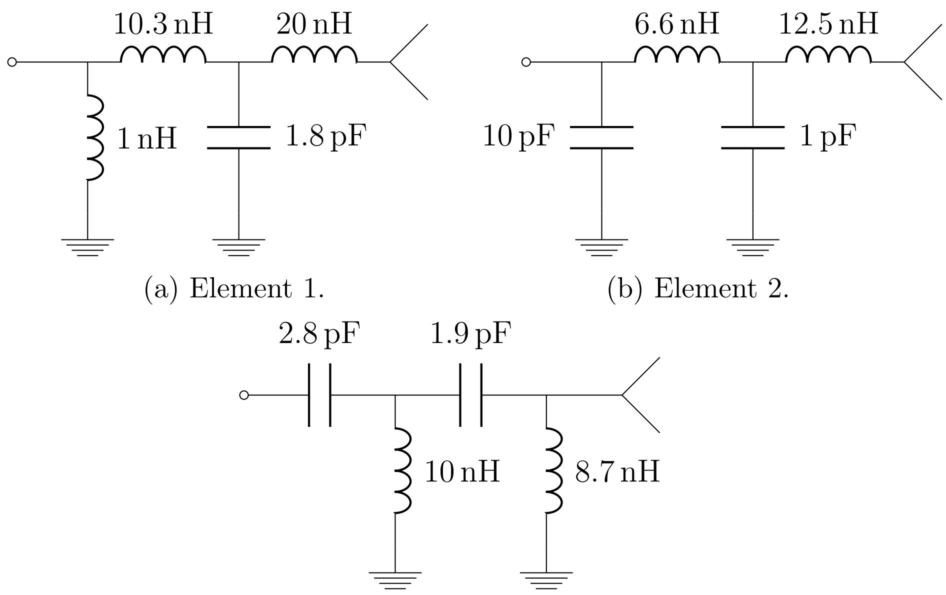


(a) Matching of each element. (b) Mutual coupling.

Figure 41: The performance of the final concept before adding matching circuits.

For matching the antennas, the method is to mismatch other elements from the operational band to reduce the unwanted coupling, and then match the radiating element. This is done with the help of antenna's impedance plots on the Smith chart. Location on the chart shows whether a capacitance or an inductance should be added to the circuit. With the help of Optenni Lab, many different topologies and goals for matching can be tested quickly. The actual design and optimization of matching networks is done in AWR.

Though a goal for the matching level has been defined for this thesis, the target for efficiency is thought to be more important. Even if antennas are nearly perfectly matched, they might be very inefficient and thus, will not radiate. So, it is more critical to fulfill the goal for efficiency, although it means that matching level probably will not be sufficient. After many different matching circuits tested, two promising topologies are found. The first option, presented in Figure 42, has four components for each antenna element, and the only radiating element is Element 3. The other two are blocked and used only to increase bandwidth through coupling. The second possible design is shown in Figure 43. This topology oppositely blocks Element 3, and Element 2 radiates in the low band and Element 1 in the high band. From now on, the matching circuits of Figures 42 and 43 are referred to as Topologies 1 and 2, respectively.

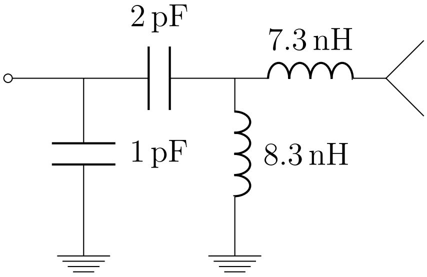


(a) Element 1. (b) Element 2.

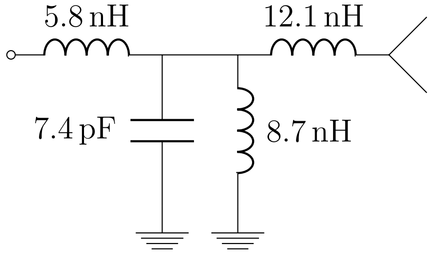
(c) Element 3.

Figure 42: The first option for matching circuitry (Topology 1). Only Element 3 radiates with this design.

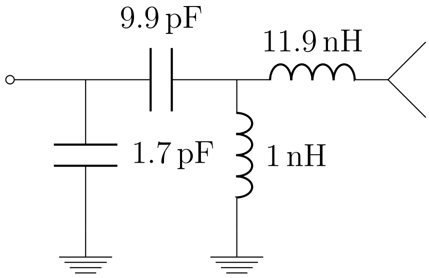
The efficiencies for Topologies 1 and 2 are presented in Figures 44a and 44b, respectively. Topology 1 gives higher maximum efficiencies, but Topology 2 covers the operational bands better. Topology 2 covers the low band totally, and only a small set of the highest frequencies is below the required efficiency of 30 %. The minimum of that part is ca. 27.5 %, which can be considered close enough at this point. Other thing to support continuing with Topology 2 is the shape of the curves, which are much smoother than with Topology 1. Smoother curves provide more stable efficiency throughout the band, which leads to improved overall performance.



(a) Element 1.



(b) Element 2.

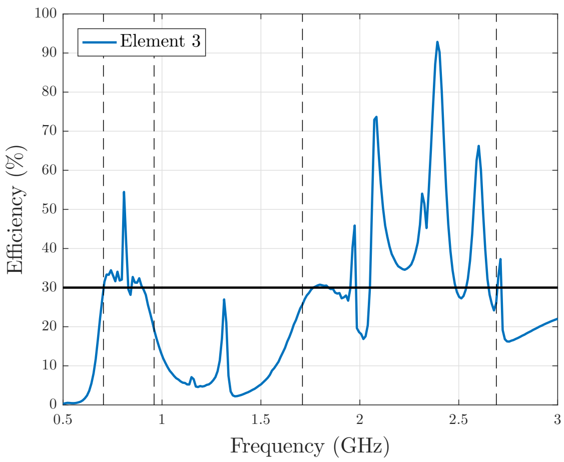


(c) Element 3.

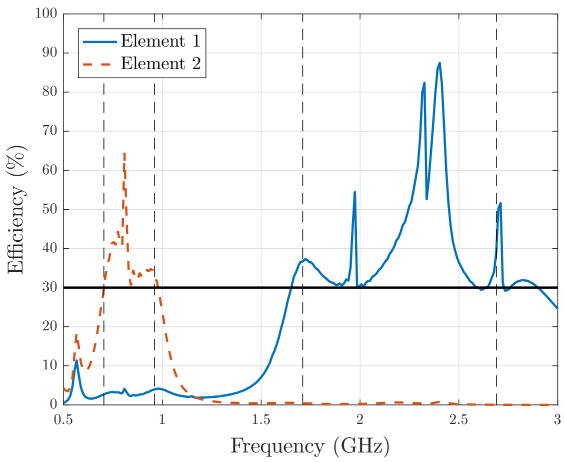
Figure 43: The second option for matching circuitry (Topology 2). Element 3 is blocked, and Elements 1 and 2 radiate.

All three elements are not shown in the figures, as one or two elements are blocked with matching circuits.

In the next steps, Element 1 will be used for communications in the high band (1.71–2.69 GHz), and Element 2 in the low band (704–960 MHz). Having distinct elements for different bands is also one reason supporting the use of Topology 2. The performance can now be optimized in more organized way, and the whole structure is simpler to understand.



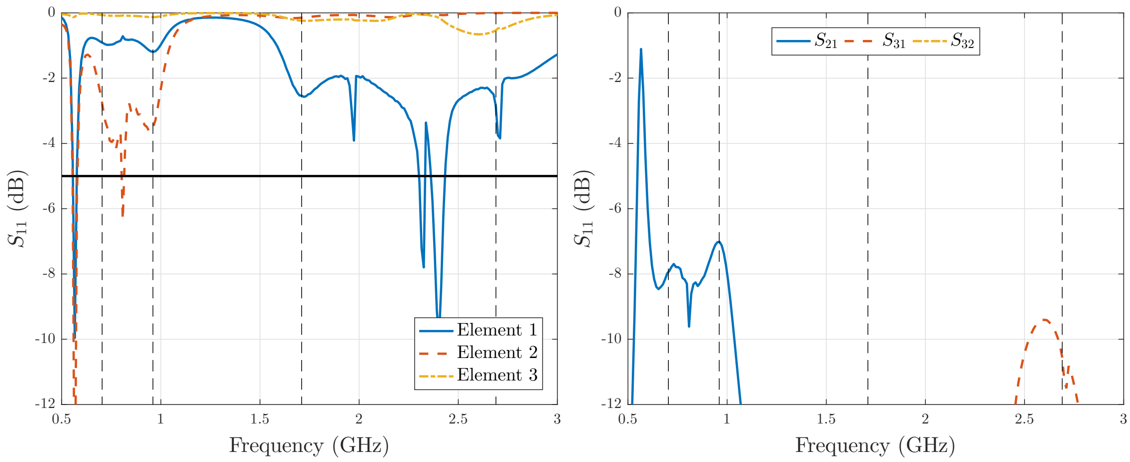
(a) Topology 1.



(b) Topology 2.

Figure 44: The efficiencies for the main antenna with the two different matching networks.

Now the main antenna has a decent performance in both the low and the high band covering them both almost completely. The matching levels with these circuits are presented in Figure 45a. The levels are below the target level, but that can be considered to be acceptable as long as the efficiency requirement is fulfilled. The levels are anyhow fair, especially in the low band. Figure 45b shows, that adding the matching circuits helped with the mutual coupling problem as the Element 3 is completely blocked. The antenna is able to radiate on a wide range of frequencies, as Figure 44b shows.



(a) Matching levels.   (b) Mutual coupling.

Figure 45: The performance of the matched main antenna.

5.2.2 Diversity antenna

The phone is specified to have two cellular antennas, operating at the same set of frequencies in order to be MIMO capable. Since the diversity antenna should have similar performance as the main one, the same structure is used also for this antenna. The main antenna is rotated 180° and placed to the other end of the phone. However, due to the USB-port and the touchpad buttons, exactly the same structure cannot be used, but the basic concept remains the same.

Since the main antenna is already an optimized structure, only a little fine-tuning is required for the diversity antenna. Figure 46 shows the final structure of the diversity antenna, and the values of the labeled dimensions are listed in Table 10. The most noticeable difference is the locations of the feeds. The differences between the distinct ends of the phone cause the optimal feed locations to be different.

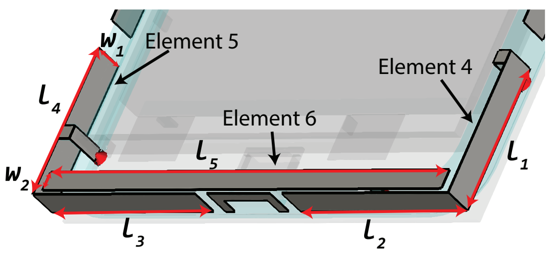


Figure 46: The structure of the diversity antenna.

Table 10: The dimensions of the final diversity antenna.

Dimension	**Value** [mm]
l_1	22
l_2	30
l_3	30
l_4	23.23
l_5	72.8
w_1	4.35
w_2	2.9

Due to the similarity to the main antenna, the same matching topologies are applied, and only the component values are reoptimized. Figure 47 shows the circuits with the component values for each element.

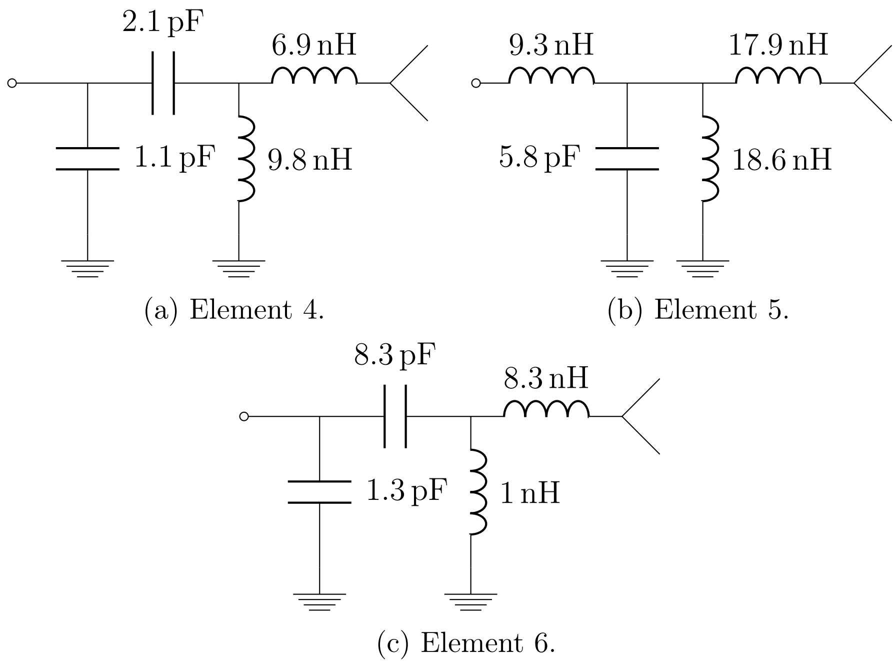
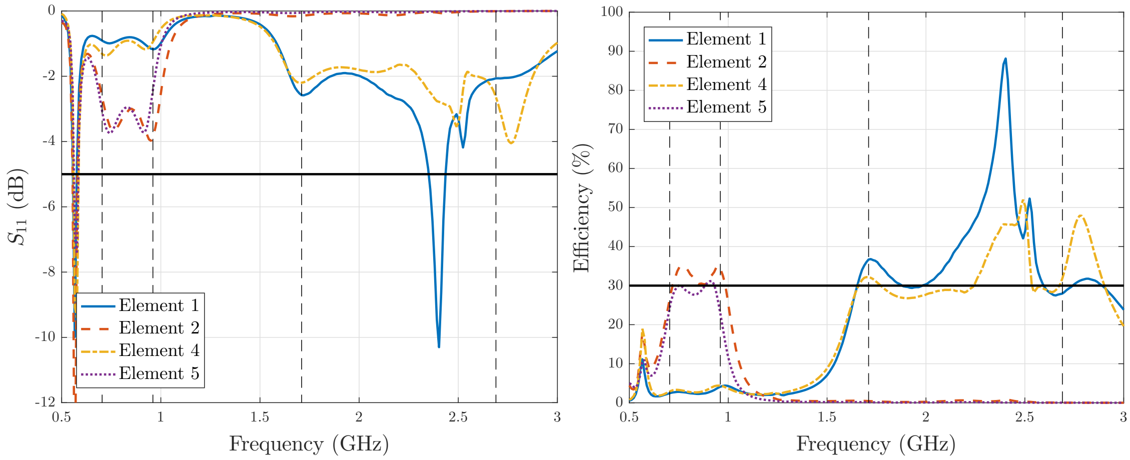


Figure 47: Matching circuits for the diversity antenna. Similarly to the main antenna, Element 6 is blocked, and Elements 4 and 5 radiate.

Figure 48a shows that the same matching topologies are usable also for this system. The target level is not reached at either of the bands, but on average the levels are decent. The most interesting discovery is that the main antenna is affected only a little by the diversity antenna. The basic shape of the response is the same and only the sharp spikes have disappeared.

The efficiency of the system behaves the same way, as Figure 48b presents. Both antennas more or less reach the target efficiency over the whole bands. As the antenna structures are now complete, the focus in the design of cellular antennas is passed to the matching circuits. Even though the existing topologies operate fine, they are far too complex. The number of components should be reduced for better understanding of the system, and also for easier realization of the system.



(a) Matching levels.

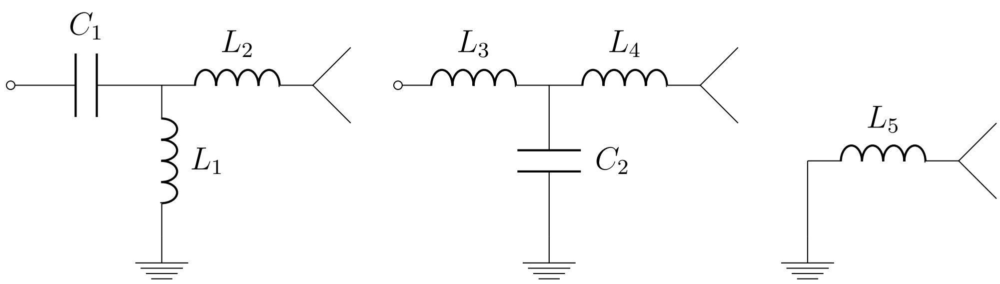
(b) Efficiencies.

Figure 48: The performance of the cellular antennas.

5.3 Improving the matching circuits

Having four circuit components for each antenna element is a lot, especially when the system totally has six elements. Finding matching circuits with fewer components would be beneficial for a couple of reasons. First, the total complexity of the system reduces, and that way the behavior of each component and element can be understood more thoroughly. Second, the system is more cost-effective and manufacturable when realized.

By taking a new look at the designed matching circuits, it can be noticed that there are some unnecessary components. Large capacitors or small inductors behave electrically like short circuits, and likewise, small capacitors or large inductors like open circuits. These electrical equivalences are applied to the designed topologies, and the new circuits are resimulated to obtain more suitable component values to preserve the performance levels. Figure 49 shows the significantly simplified topologies. As the original component values are quite similar in the main and the diversity antenna, the same modifications can be applied for both of them. The most curious change is that Elements 3 and 6 are not fed anymore, but they are reactively loaded (Figure 49c). As these elements are not used for radiation, but to enhance the performance of other elements, this new matching topology does not cause any problems.



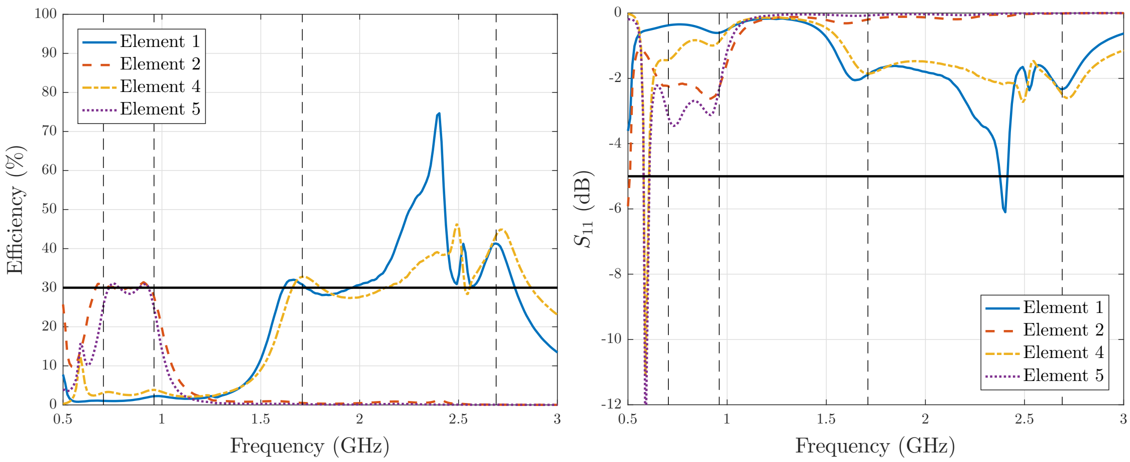
(a) Elements 1 and 4.

(b) Elements 2 and 5.

(c) Elements 3 and 6.

Figure 49: Simplified matching circuits.

The new component values are shown in Table 11 later on. With the new topologies, the antennas have slightly worse performance than with the complex ones, which can be seen if Figures 50a and 50b are compared with Figures 48a and 48b. However, as the differences are so small, and the requirement for efficiency is still nearly met, these new topologies can be considered better due to the reduced complexity.



(a) Efficiency. (b) Matching.

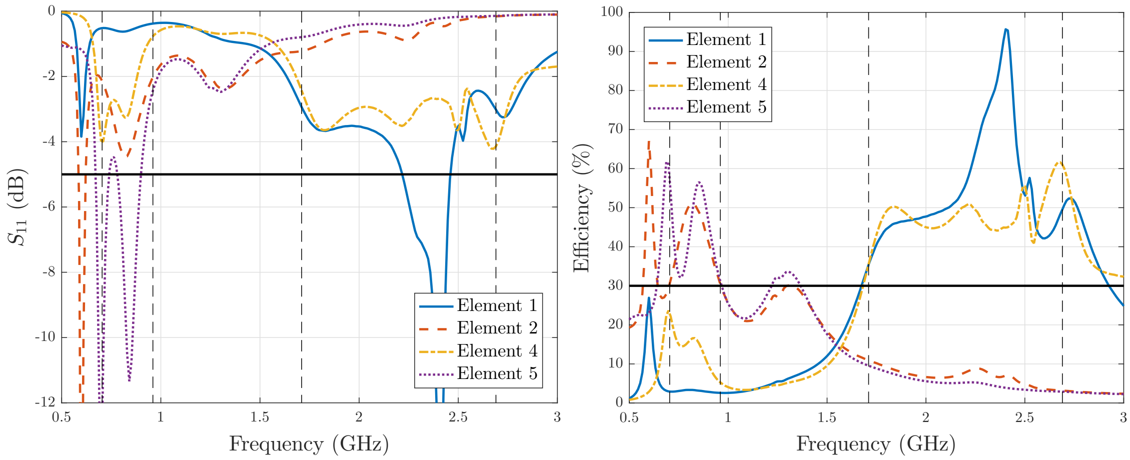
Figure 50: Antenna performance after simplifying the matching networks.

So far all the matching components have been ideal capacitors or inductors. In order to have a better view of the actual performance of these antennas, the components are replaced with realistic models of capacitors and inductors manufactured by Murata [77]. The used components are chosen from GQM1884 [78] and LQP03 [79] series. Their values are listed in Table 11, together with the previously mentioned ideal components. Realistic component models have internal parasitic capacitances and inductances, and introduce losses to the circuit. These features affect the performance of the antennas, which is the reason for differences in component values between the ideal and the realistic models.

Table 11: Component values for the matching circuits of Figure 49.

Component	Ideal components		Realistic components	
	Main antenna	Diversity antenna	Main antenna	Diversity antenna
C_1	1.1 pF	1.4 pF	1.3 pF	1.5 pF
C_2	3.9 pF	3.7 pF	2 pF	2 pF
L_1	13 nH	10.5 nH	8.2 nH	6.8 nH
L_2	8.2 nH	4.1 nH	5.6 nH	1.8 nH
L_3	8.7 nH	11.7 nH	9.1 nH	10 nH
L_4	14.4 nH	19.9 nH	10 nH	13 nH
L_5	14 nH	9.2 nH	9.1 nH	6.8 nH

Changing from ideal components to realistic ones has a major effect on the performance of the antennas. Due to the losses of the lumped elements the antennas' matching levels are improved significantly. The plots of Figure 51 show that both antennas are operating on a wide band on good levels, and fulfilling the requirements for efficiency. On average the efficiencies are around 40 % in the low band and around 50 % in the high band. Moreover, the matching levels over the whole bands are on average below −3 dB, which is clearly better than any designed antenna in this project has reached so far.



(a) Matching levels. (b) Efficiencies.

Figure 51: The performance of the cellular antennas with realistic matching components.

With the above presented results, the design of cellular antennas is finished. In the next part, the whole design process is finalized with antennas for GPS and Wi-Fi.

5.4 Finalizing the design

As the cellular antennas are integrated into the side metals at the ends of the phone, the most logical and the only possible locations for GPS and Wi-Fi antennas are the metals on the long sides of the handset. With this placement of these antennas the metallic side frame would be utilized nearly completely for communications purposes.

5.4.1 GPS and Wi-Fi antennas

As Wi-Fi operates on higher frequencies (2.4 GHz and 5 GHz bands), the required antenna element can be rather short. However, GPS uses lower frequency, 1.575 GHz, and thus requires a longer antenna. The structure is desired to be kept as simple as possible, and therefore the I-shaped elements for GPS and Wi-Fi are combined by a 0.5 mm slot. The feed is placed on the shorter part and currents couple from that to the other one. To improve the available bandwidth, the antennas are enlarged in width, and a part of them is bended to lie on the front face of the handset. The structure is illustrated in Figure 52.

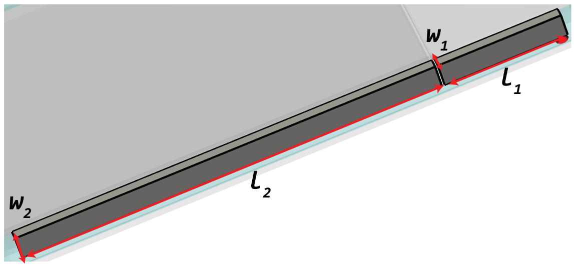


Figure 52: The structure of the GPS/Wi-Fi antenna.

The other required antenna is implemented on the metal frame on the opposite side of the phone. The two antennas have only a small dimensional difference, which is listed along the other labeled dimensions in Table 12. Element 7 refers to the antenna seen in the figure above, and Element 8 is on the other side of the phone.

Table 12: The dimensions of the GPS/Wi-Fi antennas.

Dimension	**Element 7** [mm]	**Element 8** [mm]
l_1	23	23
l_2	78.27	77.51
w_1	2.11	2.11
w_2	4.35	4.35

Since the matching circuits of the cellular antennas have quite many components even after the simplification, it is decided that L-section matching would be used for GPS and Wi-Fi antennas. It is found out that series capacitor and parallel inductor provide the desired matching for these antennas. Topology is seen in Figure 53. The realistic component values are $C_3 = 2\,\text{pF}$ and $L_6 = 6.8\,\text{nH}$ for both elements.

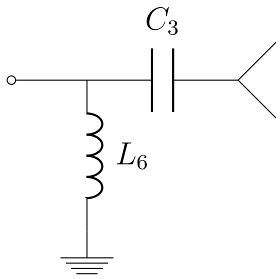
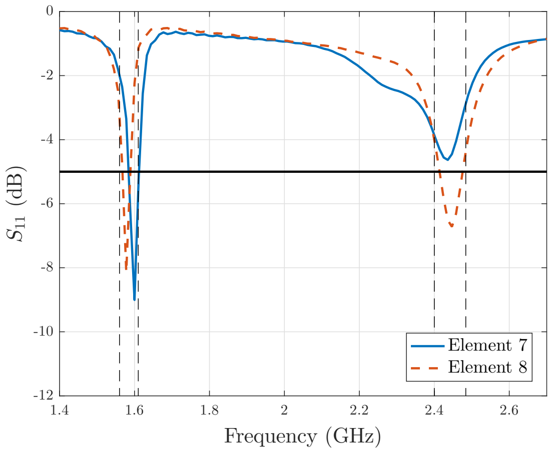
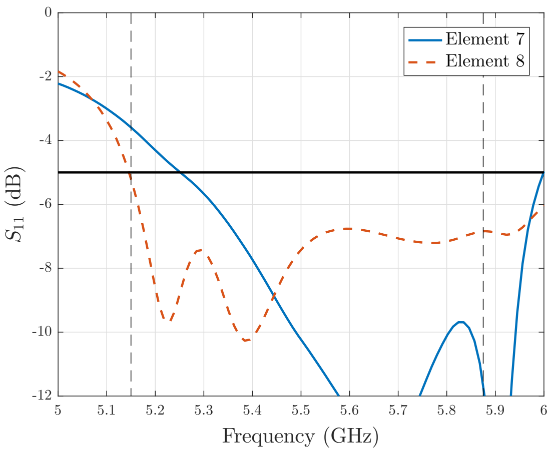


Figure 53: The matching circuit for GPS/Wi-Fi antennas.

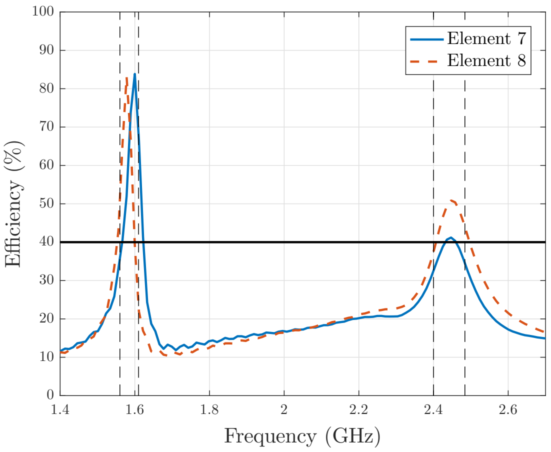
The performance of GPS and Wi-Fi antennas is seen in Figure 54. Matching levels are shown in Figures 54a and 54b respectively for GPS and 2.4 GHz Wi-Fi, and 5 GHz Wi-Fi. Similarly to cellular antennas, the target matching level of $-5\,\text{dB}$ is not fully reached over the whole band for both antennas. However, the efficiencies are much better and the target of 40 % is mainly reached, as Figures 54c and 54d present. The only exception is the other 2.4 GHz Wi-Fi antenna, which just barely peaks to 40 %. Also, neither of the GPS antennas does not cover the whole 1.575 GHz band, but since the phone is equipped with two of those, the band is covered completely.



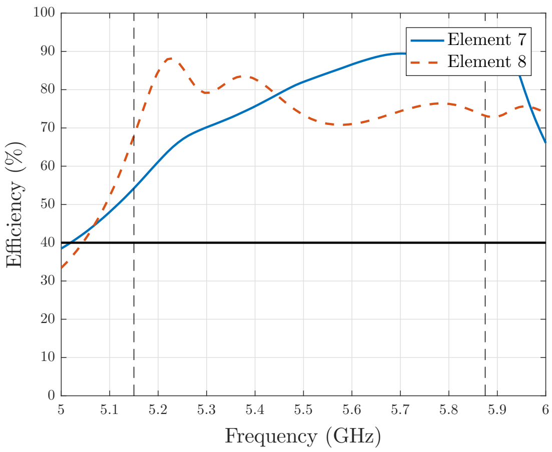
(a) Matching.



(b) Matching.



(c) Efficiency.



(d) Efficiency.

Figure 54: The performance of the GPS/Wi-Fi antennas.

5.4.2 Complete structure

With the GPS and Wi-Fi antennas added to the phone, the design project is now complete. Figure 55 shows an overall view of the phone and how the antennas locate on it. All the antennas are integrated into the metallic side frame, which will save some space inside the phone for other subsystems and parts of the device.

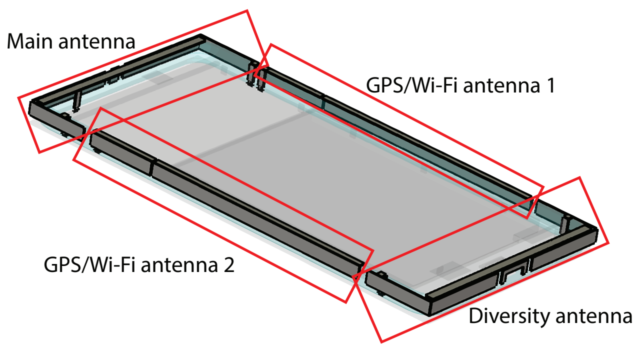
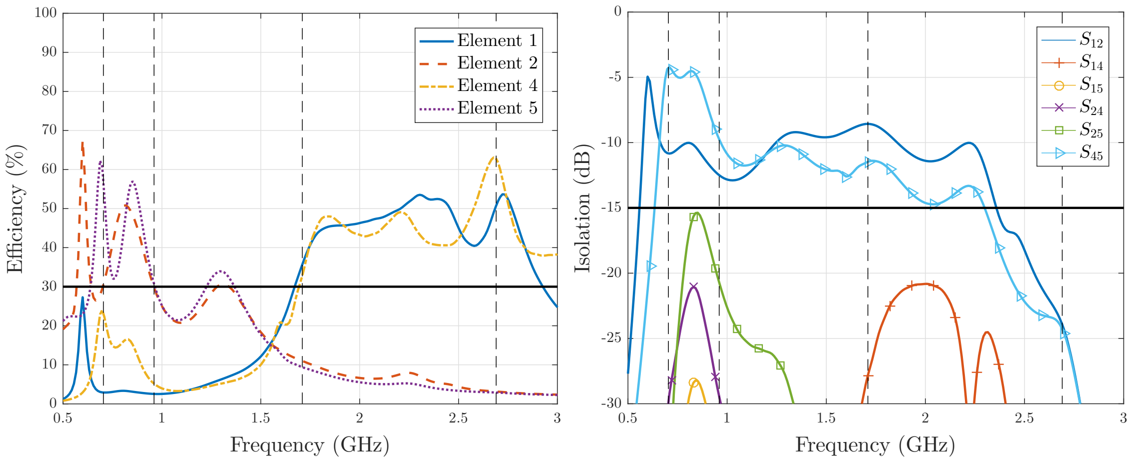


Figure 55: The complete structure highlighting the locations of the antennas.

The addition of the GPS/Wi-Fi antennas has a minor effect on the performance of the cellular antennas. Figure 56a shows the efficiency of these antennas after the addition of the other elements. The performance targets are still met, and the most noticeable difference is basically the worse peak value of Element 1, which is still over 50 %.

Project goals also have a requirement for the isolation between the main and the diversity antennas. The target level is −15 dB, which practically means that no power flows from one antenna to the other. The isolation between the elements of the cellular antennas is presented in Figure 56b. In the figure, various S_{ij}-parameters are shown, and indexes i and j refer to the antenna elements from or to which the power is scattered. Clearly, these antennas are well isolated as all combinations are below the target value.

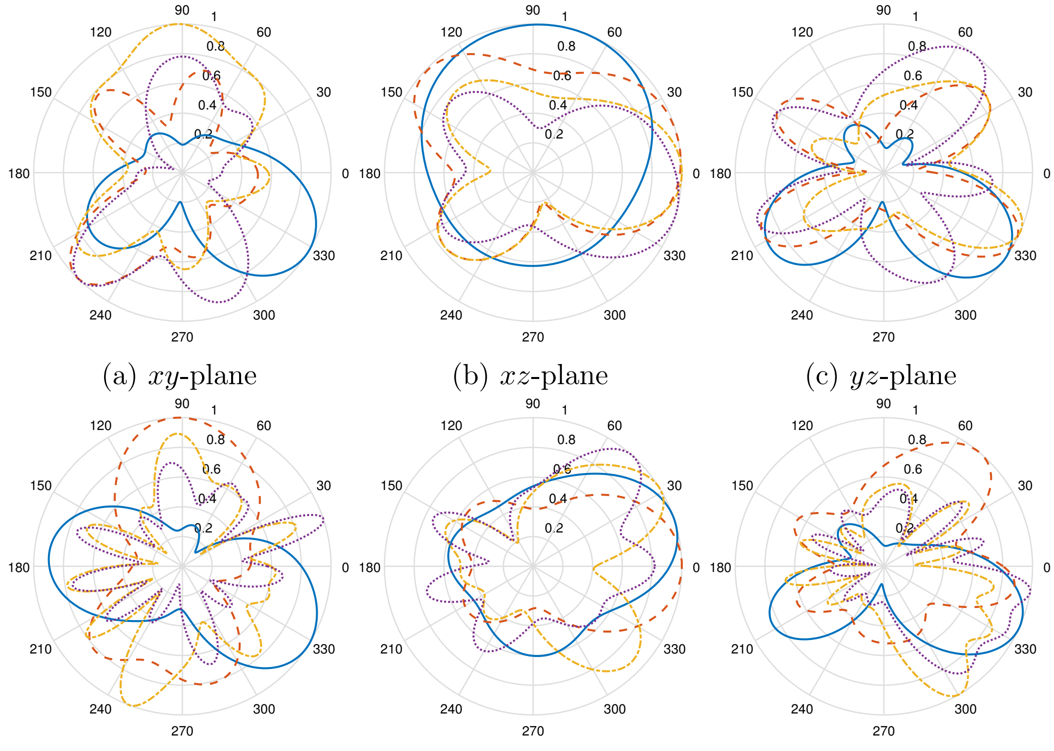
In the same figure, the internal isolations (or mutual couplings) of either the main or the diversity antenna are also plotted. These S_{12} and S_{45} curves do not reach the target isolation of −15 dB except at the very highest frequencies. However, that target is only for separating the main and diversity antenna from each other. The internal isolations are mainly below or around −10 dB, which is acceptable. The only problematic part is the low band of the diversity antenna, where power is leaking between Elements 4 and 5, causing lower efficiencies as seen in Figure 56a. Element 4, which is planned to radiate only on the high band, has an efficiency of 20 % in the low band as well. Otherwise this would not be a problem, but this performance affects the main low band radiator of the diversity antenna.



(a) Efficiencies. (b) Isolation.

Figure 56: The final performance of the cellular antennas.

The last results to be reported are the radiation patterns. For mobile phones, omnidirectional patterns are desired due to the fact that users should be able to communicate without a need to point their phones to a certain direction. Figure 57 presents the patterns for a few frequencies on xy, xz, and yz-planes. To clarify the patterns, Figure 58 shows the orientation of the phone in the coordinate system.



(a) xy-plane (b) xz-plane (c) yz-plane

(d) xy-plane (e) xz-plane (f) yz-plane

Figure 57: Radiation patterns of the designed antennas. In Figures 57a–57c, the continuous blue, dashed red, dash-dotted yellow, and dotted purple lines are the patterns at cellular frequencies 830 MHz, 1.9 GHz, 2.3 GHz, and 2.5 GHz, respectively. Accordingly, in Figures 57d–57f the lines in the same order represent GPS/Wi-Fi frequencies 1.575 GHz, 2.4 GHz, 5.15 GHz, and 5.5 GHz.

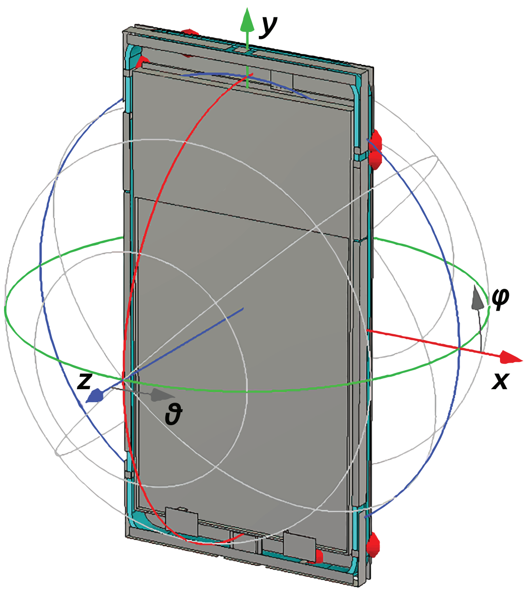


Figure 58: The orientation of the phone in the coordinate system.

The figures show that the patterns are not totally omnidirectional. However, at each of the plotted frequencies, some power is radiated to all directions, which is the most important observation of these patterns. Furthermore, the best omnidirectionality is achieved in xz-plane, which is the most relevant one considering the orientation of the phone in the coordinate system, and how the device is held in talking position. Like Section 3.2 presents, the previously studied structures have a good omnidirectionality, especially the ones with a metal cover. However, this proposed structure has the continuous metal as the back cover, which distinguishes the designs from each other. The large number of metallic parts in the phone together with the large metallic back cover make it extremely difficult to achieve omnidirectionality, due to their conductive nature. Moreover, the other properties of a mobile antenna are more important to focus on during the design process. By nature, the designed antennas have somewhat omnidirectional patterns, and thus, it is more critical to optimize other design goals.

6 Analysis of the proposed antennas

The results are only explained in the previous section, and some conclusions are made based on them for the next simulation round. This section provides more thorough analysis of the results and the structure itself. The designed antennas are analyzed by both technical and general aspects. The last part of this section discusses possible improvements to this structure.

6.1 Fulfillment of objectives

Cellular antennas are designed to operate on both 704–960 MHz and 1.71–2.69 GHz frequency ranges. Additionally, two antennas to support GPS and Wi-Fi connections are designed. Each antenna should be matched to −5 dB, and have a certain efficiency. The minimum efficiencies are 30 % for cellular and 40 % for other antennas. Also, the isolation between the two cellular antennas should be at least −15 dB.

The final structure indeed has all four required antennas, which are all performing quite well. Obtaining the desired matching level is the most problematic part, and as is seen in the results, the target is mostly not reached. The best matching levels are achieved in the 5 GHz Wi-Fi band. However, as it is explained earlier, worse matching is accepted if efficiency target is reached. As the efficiency results show, those targets are reached by cellular antennas, and nearly reached by other antennas. The efficiencies are calculated with (4), and thus it must be remembered that the results are only approximations. They can be anyway considered quite accurate as the only lossy parts of the simulation model are the plastic rim and the matching components.

The only antenna not reaching the efficiency target is Element 7 at 2.4 GHz Wi-Fi band, which has the peak efficiency only a little above the target. However, this probably would not be a problem if this antenna was used in a consumer product, as the other Wi-Fi antenna is working fine, and also the performance of the cellular antennas is good at that frequency range. If needed, one of the cellular antennas could be used also for WLAN communications. The GPS antennas, on the other hand, have proper efficiencies, but their bands are a little too narrow. Fortunately, the whole GPS band is covered as the operating frequencies of the two antennas slightly overlap.

Besides efficiencies, also the isolation of cellular antennas is under interest. As it is presented, the two ends of the phone are not interfering with each other, as the target isolation is reached for all elements at all operating frequencies. A little negative discovery is the internal isolation of both the main and the diversity antenna. Those do not have any target, but the isolations are not that good, which is seen as decreased efficiency, especially for the diversity antenna. Even though it is desired that the antenna elements couple strongly, power should not flow to the ports of other elements. However, as the efficiencies are good, this is not a major problem.

Generally, the design objectives are fulfilled very well, and the antennas are operating as desired. Of course, the performance can always be improved, which is discussed further in Subsection 6.4.

6.2 General discussion

Besides analyzing the accomplished objectives, the results of this project should be compared to previous studies, and have its advantages and drawbacks evaluated.

One significant difference between this project and all the earlier presented, previously published papers is the simulation model. As far as the author knows, using as realistic model as this one is not reported in scientific literature. This increases the value of these obtained results, as they might correspond better to the consumer products. However, the realistic model is also a drawback, and complicates the research process. Constructing a prototype is much harder, and the matching circuits with several components are not making it easier. Measuring a prototype antenna is an important part of the design process to confirm the simulation results, and also to see if the structure is realizable.

The designed structure has a few clear advantages. The first one is the back cover. Only two of the most recent studies have a solid and slotless back cover. Typically, at least one slot or opening is used to enhance radiation, and simplify the problem. For this thesis, it is described to use a cover without any discontinuities. This detail together with the accuracy of the simulation model makes the environment and the case completely different from previous studies.

Secondly, using the side metals as antennas is not a new idea, but it is a general advantage, as that technique frees up the already limited space inside the phone for other subsystems. However, as the antennas are integrated into the sides, it makes the rim broken at several locations. This might be bad for the robustness of the phone compared to the strength of an unbroken rim. Also, the antenna elements themselves are quite large, which is fine due to the structural integration, but in case of an impact, they might be more likely to become damaged.

Also, this design is fully MIMO capable, which is a clear advantage over the previously studied antennas, as only a few of them are capable of MIMO communications.

The performance of this designed system is competitive against the previous studies, regardless of the structural differences of the models. The most remarkable detail is the frequency band, which in this case starts from 704 MHz. Only a couple of the earlier reported designs support that low frequencies. The cellular efficiencies of the designed antennas are at a range of 30–60 %, which is comparable with that of previously studied metal-covered handsets have.

6.3 MIMO capability

In a modern mobile phone, it is common to have multiple antennas for the same frequencies, i.e. to support MIMO techniques. This project aimed at a cellular MIMO antenna. The simulation results presented in Section 5.4.2 show that the main and the diversity antenna both reach the efficiency target easily. As the structure does not have any tuners or switches, these two antennas are able to communicate simultaneously. Also, the antennas are well isolated, and thus they do not interfere with each other.

As Section 2.8 explains, envelope correlation coefficient can be used to evaluate MIMO capability of a mobile phone besides efficiency, matching, or isolation. EEC is calculated for both the low and the high band with (13). Again, as this structure has some losses in the plastic rim and matching components, the calculated value will only result in an approximation of the coefficient, which is seen in Figure 59.

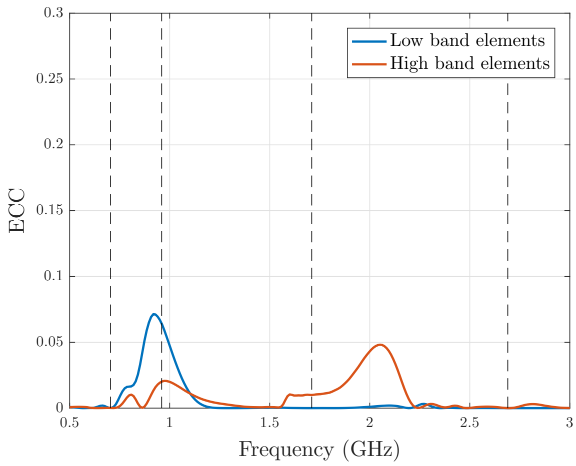


Figure 59: Envelope correlation coefficient for low and high cellular bands.

The ECC curves confirm the observations from the other results. Generally, $\rho_e \leq 0.5$ is considered as good performance, and in this case the ECC is clearly below 0.1 in both bands. Moreover, the correlation is near 0 for the most of the operating bands, meaning the two antennas are completely uncorrelated. Therefore the MIMO capability of this design is remarkably good, as the antennas radiate well, and do not affect negatively each other.

6.4 Possible improvements and future work

Even though the proposed design performs well, the system can still be improved. The next main step would be constructing a prototype to confirm the simulation results. In order to do that and realize the design, one major challenge is the matching circuitry. Although the networks are simplified a lot, the topologies still have rather many components. With fewer components it is easier to control the performance, and realizing the design becomes significantly simpler. Possible solutions for this would be for example tunable capacitors. Using DTCs would not necessarily improve the overall performance, but matching circuits might operate decently with fewer components. In order to use DTCs, the current matching networks would require a complete reconstruction. Other way could be to investigate further the Topology 1 proposed in Section 5.2 to see if that design could be simplified. By looking the proposed component values, it does not seem to be impossible to have only single feed port with the other two elements being reactively loaded elements. This might notably decrease the number of matching components. In that case, only one element would radiate, which might yield slightly decreased performance due to the large frequency range to cover, but the system would be much simpler.

Changes in the actual antenna structure should also be considered. One potential structure would be having multiple feeds on one single element, as is proposed in [65]. In that design, each feed is matched for some frequency band, and that way one element radiates at all desired frequencies. The antenna in that paper, however, is not tested in a metal-covered phone, which makes it worth trying a similar design.

Minor modifications would consider the appearance of the phone, if a consumer product was manufactured. Of course the simulation model is quite harsh, and the actual phone would look nicer, but the antenna design has some visually unappealing details. For example the gaps between different antennas are not constant and are located non-symmetrically. This small matter should be investigated, since even the smallest dimensional changes might affect a lot on antenna's performance, as it is seen in the simulations.

Hand-effect may be the the most significant thing that has not been studied in this thesis. Mobile phones are mainly kept in hands when used, and also located very close to the user's head when a call is on-going. This effect is studied widely, and also included in many of the papers referenced in Section 3. The simulation model used in this project is already challenging due to the metallic back cover and other parts of the phone that are modeled as metal blocks, and adding user's hand or head to this environment would complicate the simulations a lot. That is anyway an important detail to test due to the fact that phones are mainly used in a close proximity of a person. Without researching that effect, it is impossible to tell for sure if the designed structure is actually usable in practice.

7 Summary and conclusions

In this thesis, antennas for metal-covered handsets have been studied. The work consists of two parts: literature review on previously studied antennas and an antenna design. The main objectives of this work are to design antennas for a mobile terminal with unbroken metallic back cover, and to understand the challenges in the design process caused by the cover.

As the wireless networks have developed and the volume of data traffic has simultaneously increased, more and more is required from the mobile terminal. Desires for better robustness and aesthetics by using metal covers significantly increase the complexity of the system from an antenna design point of view. The network requires antennas to communicate efficiently on a wide frequency band, but the metal structures disturb this. Traditional mobile phone antennas, e.g. PIFAs, placed inside the phone are strongly affected by the surrounding conductive materials.

Majority of the previous studies on this topic have only a metallic side frame, and in the few studies that have also back cover, slots have been cut into it. Antenna structures proposed in the previous studies have had decent performance, but the mechanics of them are rather complex. This thesis differs from those studies as the back cover of the handset is a single continuous metal plate. Also, the designed antennas have quite simple structure, and they are integrable into the metal frame on the sides of the device.

Considering the challenging environment due to the metal cover, the performance targets defined by AAC Technologies are quite strict and challenging to achieve. The two cellular antennas are supposed to operate at 704–960 MHz and 1.71–2.69 GHz, have at least 30 % efficiency, and be fully MIMO capable. Additionally, the two GPS/Wi-Fi antennas should have at least 40 % efficiency. As a remark, only a minority of previous studies support the 700–800 MHz cellular band, or MIMO.

Designing the antennas is done in an electromagnetic simulator. The model of the phone is based on a mechanically accurate 3D-model of a real phone. This model is significantly more detailed than the models published in the previous studies. Nevertheless, a suitable antenna structure is constructed. The designed cellular antennas consist of three closely located elements, in order to have strong mutual coupling to increase bandwidth. The designed matching circuits are also critical to the system. Without them, the results show that the antennas would not radiate at all. Now, the proposed structure results a good cellular performance, and fulfills the design targets. Generally, the performance of the designed antennas corresponds with the project requirements.

The metal cover makes it difficult to obtain good and wideband matching. Large conductive plate at a close proximity causes the response to be very peaky with rather narrow bands. As all the antennas are integrated to the side frame of the phone, finding good locations for each of them is quite simple, as is determining the optimal dimensions to have the antennas operating at correct frequencies. Finding suitable matching circuits to reach sufficient performance is the challenge. Based on the results it is understandable why many of the previous studies have slots in the back cover.

Even though this structure performs well, it can be developed further. Antennas for metal-covered handsets are still pretty little researched, especially if compared to mobile antennas in general. Metal-covered phones will become more popular in the future, simply due to their nice outlooks and robustness. Before that can happen, antennas and other communications subsystems must be able to operate according to the requirements set by the network standards.

To conclude, the presented antennas operate on all the desired frequencies (LTE, GPS, and Wi-Fi) with good efficiencies, and the cellular antennas are fully MIMO capable. The design objectives are mostly fulfilled, even though the environment is rather challenging. As a final remark, the metal cover clearly affects the antenna performance by lowering efficiency, and making wideband matching quite difficult. Nonetheless, having a mobile phone with full metal housing does not seem impossible based on these results.

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