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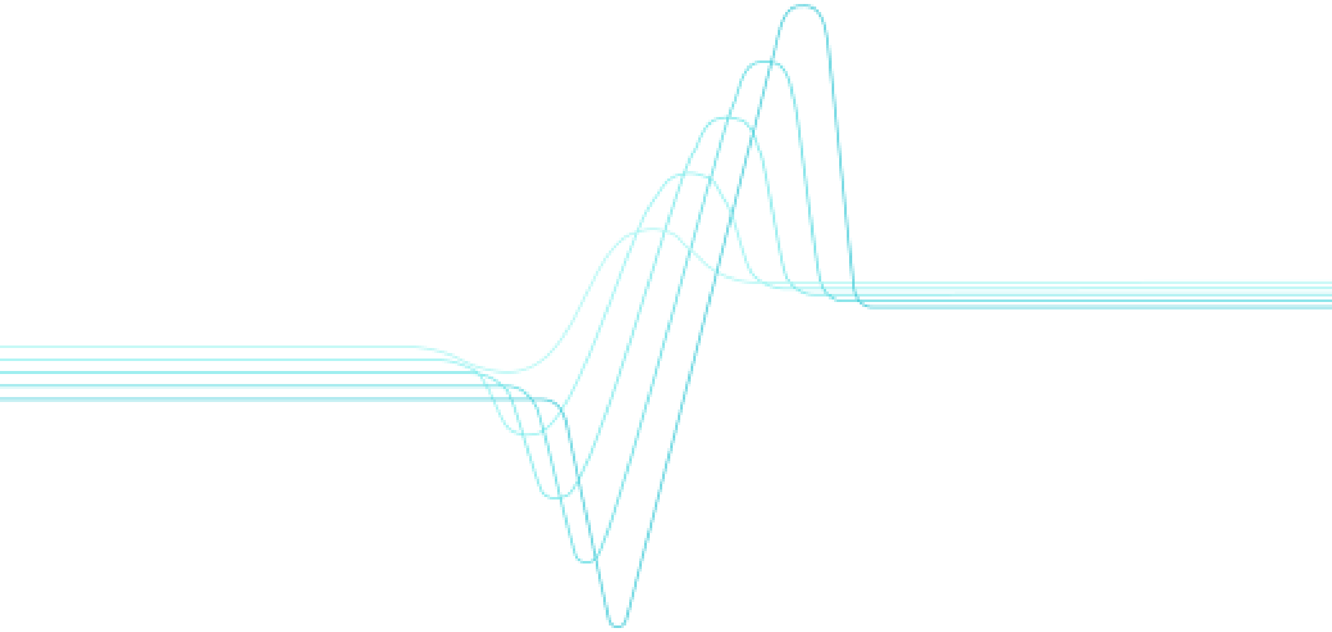

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Performance enhancement of small antennas and applications in RFID

Mervi Hirvonen

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Keywords small antennas, RFID, wireless sensors, quality factor, near-zero permittivity, non-Foster tuning, multi-port antennas, platform insensitivity, dual-band, backscattering measurement

Abstract

The focus of this thesis is on the performance enhancement of small antennas and design and verification of antennas for radio frequency identification (RFID) and wireless sensors. The work is presented in eight scientific papers and in a summary, which introduces relevant fundamental concepts and previous work done in the field of small antennas.

Previously, several performance enhancement methods have been proposed to improve the antenna performance especially in mobile communication applications. However, solutions for the fundamental small antenna problem, high reactive energy and low radiation resistance, which in practice lead to narrowband and low efficiency operation, are rarely provided. In this thesis, alternative methods to alleviate the high reactive energy and low radiation resistance like material loading, non-Foster tuning and multi-port loading are discussed.

Also, lately antennas for RFID and wireless sensor applications have gained growing interest. However, several characteristic design features exist for these antennas. Especially, the concept of platform insensitivity is essential and discussed in detail. Also, antenna designs and dual-band tuning technique applicable to RFID antennas are presented. In addition, wireless measurement techniques for RFID antenna verification are reported.

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Tiivistelmä

Väitöskirjatyö käsittelee pienten antennien suorituskyvyn parantamista sekä etälukuun (RFID) ja langattomiin antureihin soveltuvien antennien suunnittelua ja mittausta. Työ koostuu kahdeksasta tieteellisestä julkaisusta sekä yhteenvedosta, jossa on esitetty pienten antennien peruskäsitteitä sekä alan aikaisempia tutkimustuloksia.

Aikaisemmin pienten antennien suorituskykyä on pyritty parantamaan mm. matkaviestinlaitteissa. Kuitenkin ratkaisuja pienten antennien perusongelmaan, korkeaan reaktiiviseen energiatasoon sekä matalaan säteilyresistanssiin, jotka tekevät antennista käytännössä kapeakaistaisen ja hyötysuhteeltaan huonon, on harvemmin esitetty. Tässä työssä on analysoitu eri menetelmiä korkean energiatason ja matalan säteilyresistanssin lieventämiseen, kuten materiaalikuormitusta, non-Foster-viritystä sekä usean portin kuormitusta.

Viime aikoina etälukuun ja langattomiin antureihin soveltuvat antennit ovat herättäneet kasvavaa kiinnostusta. Näissä sovelluksissa antenneihin liittyy kuitenkin useita erityisiä ominaisuuksia. Erityisesti antennien alustaepäherkkyys on tärkeää, ja sitä on käsitelty työssä yksityiskohtaisesti. Lisäksi työssä on esitetty RFID-antennimalleja sekä niihin sopiva kaksitaajuusviritystekniikka. Myös RFID-antenneille soveltuvia langattomia mittaustekniikoita on esitetty.

Preface

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Mervi Hirvonen, Espoo, August 2008

List of publications

[P1] M. Hirvonen and J. C.-E. Sten, "Power and Q of a horizontal dipole over a metamaterial coated conducting surface", *IEEE Trans. Antennas Propagat.*, vol. 56, no. 3, pp. 684–690, March 2008.

[P2] M. Hirvonen and S. A. Tretyakov, "Near-zero permittivity substrates for horizontal antennas: Performance enhancement and limitations", *Microwave and Optical Tech. Lett.*, vol. 50, no. 10, pp. 2674–2677, Oct. 2008.

[P3] M. Hirvonen, A. Hujanen, J. Holmberg and J. C.-E. Sten, "Bandwidth limitations of dipoles matched with non-Foster impedances", *Proceedings of European Conference on Antennas Propagat., EUCAP 2007*, Nov. 2007.

[P4] J. C.-E. Sten and M. Hirvonen, "Impedance and quality factor of mutually coupled multiport antennas", *Microwave and Optical Tech. Lett.*, vol. 50, no. 8, pp. 2034–2039, August 2008.

[P5] J. C.-E. Sten and M. Hirvonen, "Decay of groundplane currents of small antenna elements", *IEEE Antennas Wireless Propagat. Lett.*, vol. 4, pp. 82–84, 2005.

[P6] M. Hirvonen, P. Pursula, K. Jaakkola and K. Laukkanen, "Planar inverted-F antenna for radio frequency identification", *Electronics Letters*, vol. 40, no. 14, pp. 848–850, July 2004.

[P7] M. Hirvonen, K. Jaakkola, P. Pursula and J. Säily, "Dual-band platform tolerant antennas for radio-frequency identification", *IEEE Trans. Antennas Propagat.*, vol. 54, no. 9, pp. 2632–2637, Sep. 2006.

[P8] P. Pursula, M. Hirvonen, K. Jaakkola and T. Varpula, "Antenna effective aperture measurement with backscattering modulation", *IEEE Trans. Antennas Propagat.*, vol. 55, no. 10, pp. 2836–2843, Oct. 2007.

Contribution of the author

[P1] The paper was initialized and developed mainly by the author. Dr. J. Sten participated in deriving the analytical expressions and preparing the paper.

[P2] The paper was developed mainly by the author. Prof. S. Tretyakov participated in deriving the analytical expressions and preparing the paper.

[P3] The paper was initialized and developed mainly by the author. A. Hujanen, J. Holmberg and Dr. J. Sten participated in defining the work.

[P4] The author prepared the paper with Dr. J. Sten. The author initialized and defined the application examples and performed the computations.

[P5] The author prepared the paper with Dr. J. Sten. The author initialized and defined the application examples and performed the computations.

[P6] The antenna structure presented in the paper was invented by the author. P. Pursula and K. Jaakkola participated in the backscattering measurements. K. Laukkanen supervised the work.

[P7] The antenna structure and tuning technique presented in the paper was invented by the author. K. Jaakkola and P. Pursula participated in the backscattering measurements. J. Säily supervised the work.

[P8] The paper is a result of collaborative work. The author participated in designing and defining the measured antennas as well as in the actual measurements and analysis of the results.

Contents

Appendices

Abbreviations

AUT	Antenna Under Test
DC	Direct Current
EIRP	Effective Isotropic Radiated Power
ERP	Effective Radiated Power
GPS	Global Positioning System
HF	High Frequency
IC	Integrated Circuit
ILA	Inverted-L Antenna
MEMS	Micro-Electro-Mechanical Systems
NIC	Negative Impedance Converter
PEC	Perfect Electric Conductor
PIFA	Planar Inverted-F Antenna
PMC	Perfect Magnetic Conductor
RCS	Radar Cross Section
RF	Radio Frequency
RFID	Radio Frequency Identification
TE	Transverse Electric
TM	Transverse Magnetic
UHF	Ultra High Frequency
VSWR	Voltage Standing Wave Ratio

List of symbols

a	Radius
b	Thickness
A	Aperture
B	Bandwidth
C	Capacitance
d	Length
$\mathbf{E}$	Electric field
G	Gain
$\mathbf{H}$	Magnetic field
I	Current
k	Wave number
L	Inductance
L_{retn}	Return loss
$\mathbf{n}$	Normal
n	Mode number
P	Power
Q	Quality factor
r	Distance
R	Resistance
S	Matching level
T	Coupling factor
U	Voltage
W	Energy
Z	Impedance
ε	Permittivity
Γ	Reflection coefficient
λ	Wavelength
η	Efficiency
μ	Permeability

σ	Radar cross section
ω	Angular frequency

1 Introduction

1.1 Background

Wireless technology has become a part of our everyday life. Mobile communication, GPS navigation and wireless internet connections are the most common examples. However, wireless technology has lately found new applications also in identifying products in logistics, industrial production, theft prevention, automatic payment systems and in key cards to name but a few. Moreover, integrating sensors to wireless platforms enables the distributed monitoring of the environment. Important applications can be found for example in health care, rescue and safety. For example, one could monitor the life functions of the patient wirelessly in real time. Moreover, wireless sensor networks enable efficient monitoring of the potentially hazardous environments like traffic, volcanic or avalanching regions and industrial plants.

An important part of a wireless system is an antenna. Antenna transforms the RF signal generated in the transmitter device into a free-space wave and vice versa in the receiving end of the link. However, since the past hundred years there has been a growing interest in reducing the physical size of the antenna. Rapid development in minituarizing the electronics has also led to ever increasing demand for electrically small antennas (antennas, whose largest dimension is a fraction of the free-space wavelength). Especially in modern wireless applications, such as in radio frequency identification (RFID) and wireless sensors, the antenna has usually become the largest object and defines the physical size of the device.

However, antenna miniaturisation is a big engineering challenge because of the fundamental limitations that restrict the antenna performance. In the ideal case, all the power fed to the antenna would be radiated into free space through antenna radiation resistance and no energy (reactive fields) would be stored in the structure. However, even in a theoretical case antenna contains reactive fields, which make the antenna a frequency dependent device.

Especially problematic are electrically small antennas, because of their high reactive field level and low radiation resistance. Moreover, antennas designed to operate close to a conducting surface (ground plane) suffer from similar problems, since the radiation from impressed antenna currents flowing tangentially to the surface tend to be cancelled out by the surface currents induced on the plane. In practice, high reactive field level and low radiation resistance result in a narrowband operation and low radiation efficiency due to ohmic losses that are often considerable compared to the radiation loss.

Several solutions have been proposed to overcome the problems related to small antennas especially in the mobile communication applications. These solutions often utilize external resonators and device chassis to broaden the antenna bandwidth. However, remedies for the fundamental small antenna problem, high level of stored energy and low radiation resistance, are more rarely provided.

Also, small antennas tend to be sensitive to the platform. In mobile communication applications, the platform is a fixed chassis and can be taken into account in the antenna design process. In many cases, chassis may be even exploited to enhance the radiation. However, in many novel applications like RFID, no fixed platform exists, but the antenna is attached directly to different objects or environments. Thus, a theory and antenna designs showing platform insensitive characteristics are needed.

In addition to platform insensitivity, RFID antennas posses a number of characteristic design features. In RFID, the antennas are directly matched to the reactive input impedance of the IC. Thus, the antenna is not a resonant device on its own. Also, being mass production devices, the material and manufacturing issues play an important role and need to be considered in the design process. Moreover, due to the small size and reactive impedance, RFID antennas are hard to verify with traditional measurement techniques containing the measurement cable. Instead, wireless measurement techniques need to be adopted.

1.2 Objectives and contents of the thesis

The objective of this thesis is to provide new insight and solutions to problems related to small antennas and antennas for RFID and wireless sensor applications. In this thesis, the separation between the two antenna regions, the fields assosiated with spherical multipole modes outside the smallest sphere enclosing the antenna and the internal fields, is emphasized. Alternative solutions to overcome the fundamental small antenna problem, high reactive energy and low radiation resistance, by affecting the internal fields are analysed. Also, the concept of platform insensitivity as well as new antenna designs suitable for RFID and wireless sensors are provided.

The thesis is composed of eight publications [P1]–[P8] and a summary. In general, the thesis is devided into two main parts, the first one concentrating on performance enhancement issues and the second one on RFID. In the first part, in Chapter 2, the fundamental concepts including the quality factor Q, bandwidth and efficiency of small antennas are discussed in detail. Chapter 3 deals with the performance enhancement methods of small antennas. After a brief review of basic performance enhancement methods, alternative techniques related to publications [P1]–[P4] like material loading, non-Foster tuning and multi-port loading are discussed.

In the second part, in Chapter 4, platform insensitivity of small antennas is discussed. In paper [P5] a theory for understanding platform insensitivity is proposed and in papers [P6] and [P7] antenna designs showing platform insensitive characteristics are presented. Chapter 5 concentrates on antennas for RFID and wireless sensor applications. Papers [P6] and [P7] present antenna designs suitable for RFID and paper [P8] introduces a wireless measurement technique. Chapter 6 summarises the scientific contribution of publications [P1]–[P8], and the thesis is concluded in Chapter 7.

Part I

2 Fundamental concepts

2.1 Quality factor

As discussed in the introduction, stored energy and radiation resistance, which relates to radiated power, define the performance of a small antenna element. Thus, an important measure for small antennas is the quality factor Q

$$Q = \frac{\omega W}{P}, \tag{1}$$

which is known to be approximately inversely proportional to bandwidth (see Section 2.2). In equation (1) ω is the angular frequency, W the energy stored in the reactive fields and P the loss power. In a lossless case the loss power P is the power radiated to free space P_r, which is generally given by the integral [1], [2]

$$P_r = \frac{1}{2}\Re \int_S (\mathbf{E} \times \mathbf{H}^*) \cdot \mathbf{n}\, dS, \tag{2}$$

where S is an arbitrary surface enclosing the source, dS is the differential surface element and $\mathbf{n}$, the surface normal. It is often most convenient to evaluate the power in the far-field region at a certain distance r, whence (2) can be written in spherical coordinates as

$$P_r = \frac{1}{2}\sqrt{\frac{\varepsilon_0}{\mu_0}} \int_0^{2\pi} \int_0^{\pi} (|E_\theta|^2 + |E_\varphi|^2) r^2 \sin\theta \, d\theta \, d\varphi. \tag{3}$$

According to the early studies by Wheeler [3], the antenna size, quality factor Q and efficiency were found to be trade-off features. Later Chu presented a theory,

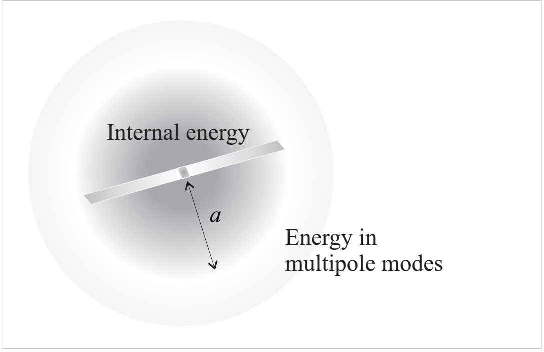

Figure 1: The smallest sphere enclosing the antenna.

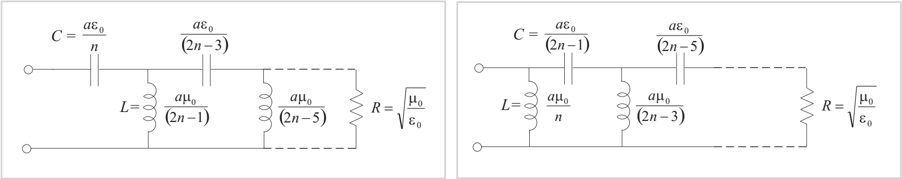

Figure 2: Equivalent circuits for spherical TM_n modes (left) and TE_n modes (right).

where the minimum quality factor of a small antenna fitting inside an enclosing sphere was derived [4]. In Chu's pioneering paper spherical harmonic wave expansions were taken to represent the fields outside the sphere and the fields inside were considered zero (see Fig. 1). Chu formulated the input impedance of the spherical fields as a continued fraction and discovered, that the radiating modes can be interpreted as a cascade of series capacitances and shunt inductances as presented in Fig. 2. As can be seen from the networks, more components are taken to model for the higher modes compared to the lower ones leading to higher level of stored energy, since [5]

$$W = \frac{1}{2}L|I_L|^2, \tag{4}$$

$$W = \frac{1}{2}C|U_C|^2, \tag{5}$$

where I_L is the local current passing through the inductance and U_C the local voltage over a capacitor. The combination of these modes would form the equivalent circuit representing the total antenna radiation, see Fig. 3. However, the power is divided to these modes by the antenna inner field, which has a major role in stored energy as discussed later in this chapter. However, in Chu's paper no representation was provided for the inner field, but it was assumed zero leading to a minimum amount of stored energy.

Finally, based on Chu's theory Collin and Rothschild presented a way to separate the propagating and reactive energy directly from the spherical wave expansion and formulated the well-known expression for the fundamental limitation of a small antenna occupying a certain volume as [6]

$$Q = \frac{1}{(ka)^3} + \frac{1}{ka}, \tag{6}$$

where a is the radius of the smallest sphere that can be drawn around the antenna and k is the wave number. In equation (6) the antenna is assumed to radiate the lowest spherical mode TM_1 or TE_1.

However, as mentioned above, Chu's theory takes into account only the electromagnetic fields stored outside the smallest sphere enclosing the antenna and

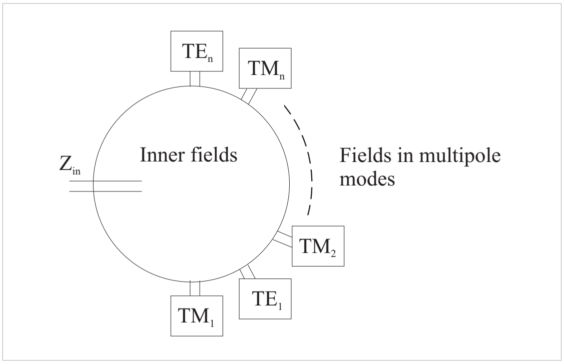

Figure 3: Antenna equivalent circuit.

assumes the fields inside the sphere to be zero. In reality, however, the antenna structure creates strong fields inside the sphere that can be considered completely stored. The total stored energy W is composed of electric W_E and magnetic W_M energies (including the effect of material dispersion) inside the smallest sphere enclosing the current carrying region (e.g. [7], [8])

$$W_{\text{int}} = \frac{1}{4}\Re \int\limits_{\text{sphere}} dV \left(\frac{\partial(\omega\varepsilon)}{\partial\omega}|\mathbf{E}|^2 + \frac{\partial(\omega\mu)}{\partial\omega}|\mathbf{H}|^2 \right), \tag{7}$$

plus the energy stored in the spherical multipole modes outside the sphere W_{ext} as given by Chu [4] and Collin and Rothchild [6]. In practice, as presented in publication [P1], the energy stored inside the smallest sphere is dominating compared to the outside energy and may be considered the performance limiting factor.

From the circuit analogy, the effect of the inner energy may be understood by adding more components to the Chu's model. For a small dipole radiating the lowest mode TM_1 an approximate circuit modeling the inner fields is introduced in publication [P3] and Section 3.2. For antennas radiating more modes, the task becomes challenging, since the power needs to be correctly divided between the modes. However, as more components form the network presenting the antenna impedance, less current fed to the antenna input port is drawn to the free-space resistances R in the radiating modes leading to lower radiated power. The same conclusion can be understood by normalizing the free-space resistances R to the feed port resistance $\Re\{Z\}$, which is the same as the radiation resistance R_r in the lossless case, whose low values lead to low radiated power.

At resonance, the electric and magnetic energies become equal. Thus, as antennas are typically considered to operate at resonance ranges, in many references, e.g. [4], [9], [10], the stored energy is often stated as two times the larger of the energies outside the resonance region as

$$W_{\text{int}} = \frac{1}{2}\Re \int\limits_{\text{sphere}} dV \left(\frac{\partial(\omega\varepsilon)}{\partial\omega} |\mathbf{E}|^2 \right), \quad \text{if } W_E > W_M \text{ and} \tag{8}$$

$$W_{\text{int}} = \frac{1}{2}\Re \int\limits_{\text{sphere}} dV \left(\frac{\partial(\omega\mu)}{\partial\omega} |\mathbf{H}|^2 \right), \quad \text{if } W_M > W_E. \tag{9}$$

However, in many modern antenna applications the antenna is directly matched to the reactive input impedance of the IC or the antenna is tuned with active components and thus, the antenna is not a resonant device on its own. Based on this, the general approach to stored energy expressed in equation (7) is considered.

Also, e.g. in [11] and [P4], the total stored energy W was shown to be related to the imaginary part of the antenna input impedance $Z(\omega)$ as

$$W \approx \frac{\partial\Im\{Z\}}{\partial\omega} \frac{|I|^2}{4}, \tag{10}$$

where I denotes the input current. On the other hand, loss power may be presented in terms of the real part of the input impedance (radiation resistance R_r in the lossless case) as

$$P = \frac{1}{2}\Re\{Z\}|I|^2. \tag{11}$$

Thus, the quality factor becomes

$$Q_z \approx \frac{\omega}{2\Re\{Z\}} \frac{\partial\Im\{Z\}}{\partial\omega}. \tag{12}$$

However, formula (12) can be applied only to small antennas with impedance level near resonance ranges. As shown in [12], a fair estimate for the Q-factor for any impedance level, even near antiresonance, may be expresssed as

$$Q_z \approx \frac{\omega}{2\Re\{Z\}} \left| \frac{dZ}{d\omega} \right|. \tag{13}$$

As presented in publication [P1], the quality factors derived either by direct integration of the energies or by taking an impedance derivative leads to well correlating results.

2.2 Bandwidth

Antenna bandwidth defines the frequency range $\Delta\omega$ where the antenna performance, usually impedance, conforms to a specified standard [13]. In other words, the impedance bandwidth is always defined with certain matching condition, for example return loss L_{retn} [5]

$$L_{\text{retn}} = 10\log|\Gamma|^2 \tag{14}$$

or voltage standing wave ratio level

$$\mathrm{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|}, \tag{15}$$

where Γ is the reflection coefficient from load $Z_L(\omega)$ to antenna $Z_A(\omega)$ as

$$\Gamma = \frac{Z_A - Z_L^*}{Z_A + Z_L}. \tag{16}$$

The antenna quality factor Q, on the other hand, only refers to the element performance itself, since no port load is considered. However, there is a direct link between the antenna quality factor and impedance bandwidth: as shown in equations (10)–(13), the higher the reactive fields and stored energy, the larger the impedance derivative of the antenna. Thus, the higher the quality factor, the more rapidly the antenna impedance varies as a function of the frequency leading to a narrowband operation.

In many references, e.g. [14], [15], the relationship between the antenna Q and the bandwidth is written as

$$B = \frac{1}{Q}\sqrt{\frac{(TS-1)(S-T)}{S}}, \tag{17}$$

where S is the matching level VSWR$< S$ and $T = \Re\{Z_L(\omega_0)\}/\Re\{Z_A(\omega_0)\}$ the coupling factor referring to the matching level at the center frequency ω_0. If the bandwidth is defined as the half-power bandwidth ($|\Gamma|^2$=0.5) and at the center frequency the matching is perfect (T=1), a well-known estimate between the bandwidth and Q, $B \approx 1/Q$, is valid. However, in equation (17) the antenna impedance is considered to be near resonance ranges, and assumed to behave like an RLC circuit. However, in reality, antennas might exhibit several resonances and contain matching circuits, in which case equation (17) does not apply.

2.3 Efficiency

Antenna radiation efficiency is defined as the ratio between the radiated power P_r and the total power accepted by the antenna P_{tot}. Radiation efficiency may be also written in terms of resistance due to the relation presented in equation (11). In practice, in addition to the radiation resistance R_r the real part of the antenna impedance $\Re\{Z\}$ contains structural losses, R_{loss}, like ohmic and dielectric losses. The radiation efficiency of the antenna is defined as [16], [17]

$$\eta = \frac{R_r}{R_{\mathrm{loss}} + R_r}. \tag{18}$$

Thus, antenna structures with a low radiation resistance often suffer from poor radiation efficiency, since the effect of even small structural losses become significant. However, as can be detected from equation (11), the antenna resistance

$\Re\{Z\}$ including both radiation and loss resistances is always normalized to the current level at that point. Thus, increasing the radiation resistance with an impedance transformer in the element (for example a folded dipole), the loss resistance increases correspondingly leading to low radiation efficiency.

3 Performance enhancement

3.1 Background

As discussed in the previous section, an important measure for the performance of a small antenna is the quality factor Q, which can be considered approximately inversely proportional to the antenna bandwidth. However, the quality factor gives information about a single radiating element, but in practice the antenna bandwidth is often affected by several resonating elements or external matching components. Thus, in principle, for example multi-stage passive impedance matching can be used to achieve bandwidths somewhat larger than the $1/Q$-estimate (see e.g. [18], [19]), but the required matching circuits tend to become very complex and are, in reality, inherently lossy.

Also, parasitic elements can be used to create multiple resonances leading to larger bandwidth performance (see e.g. [20]–[22]), but are difficult to manage due to strong coupling and added physical size. Another widely used technique is to use the antenna as a coupling element and exploit the antenna platform, like a mobile phone or GPS navigator chassis, as a radiator [23], [24]. Thus, the radiator element becomes physically larger having a positive effect on the performance. Moreover, like with passive matching networks and parasitic components, coupling element-chassis combination can be used to excite a double resonance leading to a notable bandwidth enhancement. However, in modern applications like in RFID and wireless sensors, the antenna platform is not fixed and cannot be used as a radiator. Moreover, none of these methods provide a solution to the fundamental small antenna problem: the high reactive field energy and low radiation resistance of the antenna element.

In addition to a small size, also the vicinity of the ground plane has been found to cause serious degration in the antenna performance, since the radiation from the antenna currents flowing tangentially to the surface tends to be cancelled out by the surface currents induced on the ground plane. Magnetic conductors and high impedance surfaces have been proposed to attack this problem, since in this case the induced currents would flow in the same phase enhancing the radiation [25], [26]. However, since magnetic and high impedance conductors do not exist in nature, problems arise in realization and usability of artificial magnetic conductors, because of the high profile feature and losses [26]–[28].

In the following, alternative approaches to improve the antenna performance are discussed. By material loading one can increase the radiation resistance of the element leading to enhanced radiation. Also, active impedance tuning, or non-Foster tuning, shows a very promising way to enhance antenna bandwidth properties by canceling some reactance from the antenna impedance. In addition, multi-port antennas provide new insight to the problem since their current distribution may be adjusted in a favourable way by means of distributed feeding and loading.

3.2 Material loading

Permeable materials as antenna substrates have been found to lead to lower quality factors than air and permittivity fillings [29], [30]. However, exploiting permeability is not straightforward, since natural magnetics loose their properties at higher frequencies. Lately, nanoparticle technology has been able to demonstrate higher-frequency magnetics (see e.g. [31]), but these substances are not widely available and are generally toxic. Still, permeability is also possible to achieve with artificial composite materials containing resonant inclusions, although in this case the performance is limited by dispersion. In addition to permeability, substrates containing unnatural, however also artifially tailorable, negative material parameters have been proposed in the literature to lead to enhanced antenna properties (e.g. [32], [33]).

In publication [P1], the effect of different material parameters, both natural and metamaterial parameters (ε_r <1 and μ_r <1), as a substrate for a horizontal dipole over a ground plane (see Fig. 4) was studied. From the curves denoting the radiated power P_r one could detect not only the radiation enhancement due to permeable and negative-parameter materials, but also a notable enhancement for the material, which had permittivity close to zero. Accordingly, the radiation resistance of a dipole with such a near-zero permittivity increases leading in a practical case to higher element efficiency. Moreover, while keeping the feed current constant, one could found the internal stored energy of such a system being roughly in the same magnitude compared to the air filling case leading to low radiation Q and notable bandwidth enhancement. Prior to [P1], near-zero materials were studied only to enhance the directional properties of radiated fields [34], [35].

However, in practice near-zero permittivity is difficult to implement. Like permeability at high frequencies and negative material parameters, near-zero permittivity is implemented with artificial composite materials, in this case wire grids, containing resonant inclusions (see e.g. [36]). Such materials tend to be highly dispersive, which increase the internal stored energy of the element, as can be seen from equation (7). For example, in the case of a microstrip patch antenna loaded with artificial permeability material presented in [37], dispersion was found to

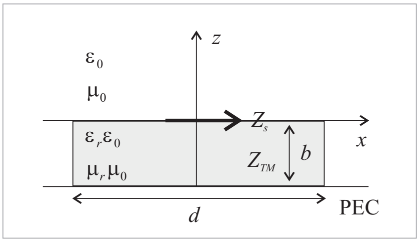

Figure 4: Horizontal electric dipole on a conductor-backed slab.

overcome the favourable enhancement leading to narrower bandwidths. Also, in [33] dispersion of negative-parameter material was found to decrease the antenna bandwidth notably.

In the case of a near-zero permittivity substrate, the favourable effect of the radiated power depends on the size of the substrate, as studied in publication [P2]. In the case of the horizontal dipole over a ground plane, the radiated power of the antenna was found to decrease drastically as the low epsilon substrate size decreases. From the surface impedance point of view, as shown in [P2], the near-zero permittivity substrate behaves partly as a magnetic conductor. As studied in [38], the near field of a wire source near a PMC spreads to a large area demanding the use of a larger screen. Also, inside the near-zero permittivity susbtrate the wavelength gets longer, and more space is needed to realize the effect.

Also, as presented in [P2], the stored energy of the element increased notably as the dispersion of a near-zero permittivity material was taken into account. As a result, the use of a near-zero permittivity substrate measuring $\lambda/4$ times $\lambda/4$ had a higher radiation Q compared to the air-filled case. On the other hand, even while including the dispersion effect, substrate $\lambda/2$ times $\lambda/2$ in size was found to already give notable enhancement in radiation Q compared to the air filling.

3.3 Non-Foster tuning

Compared to the traditional passive-component tuning, non-Foster tuning provides a whole new way to enhance the impedance performance of antennas. According to experimental results in [39]–[41], notable bandwidth enhancements have been reported. In the non-Foster technique, instead of tuning an antenna to resonance with external components, which increase the total stored energy of the system, one rather cancels the reactance seen from the input port of the antenna with negative-reactance (active) components. In the ideal case, all the reactance is canceled out and only the antenna radiation resistance is seen from the input port leading to infinite impedance bandwidth. However, in reality limitations exist.

In publication [P3] these limitations were studied. If only the energy stored outside the smallest sphere enclosing the antenna is considered, infinite bands are possible with very small dipoles by tuning the antenna with only one negative capacitance. However, in a more realistic case, the energy stored inside the smallest sphere enclosing the antenna makes the situation more complicated.

In terms of the circuit model, more components need to be included to Chu's radiation model to account for the effect of internal energy. Previously, several circuit models for small dipoles have been proposed (see e.g. [42]–[44]), but none of these makes a distinction between the inner fields and fields outside the smallest sphere. In publication [P3] a circuit model consisting of a voltage divider (two

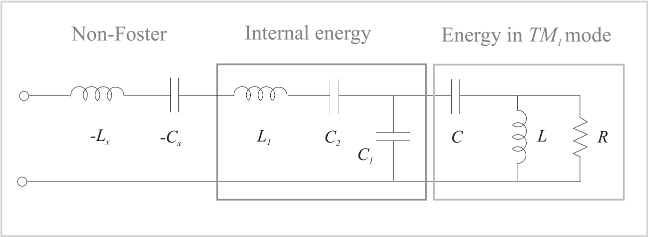

Figure 5: Approximate model for the impedance of a small dipole including the inner energy and non-Foster tuning.

capacitances) and a series inductor is proposed to model for the internal fields of a small dipole (see Fig. 5). A series inductor can be understood to relate to the physical wire carrying the current and the capacitances relate to the shunt capacitance between the dipole branches and the field capacitance tangential to the wire. Because of this voltage division, less power is drawn to the free space resistance and the element performance gets poorer compared to the case where the inner fields are considered zero.

While including the inner energy, only limited bands were achieved while tuning small dipoles with one negative capacitance. However, the bands were larger compared to the case where similar dipoles were tuned with the infinite number of passive components. On the other hand, while tuning small dipoles with two negative components, capacitor and an inductor, bands over 200 per cents were achieved.

Although these results are promising, component tolerances were found to be strict making the realization of such a system challenging. Negative-impedance components are implemented in practice with negative impedance converter (NIC) circuits, where also the performance and noise of the transistors limit the highest realizable frequency and overall performance. Moreover, power supply arrangements needed for active components make the system complex.

3.4 Multi-port elements

By feeding or loading the antenna element with multiple ports current distribution and impedance of the antenna may be modified more efficiently compared to the traditional single-port devices. The radiation Q of the antennas with multiple feed ports has been previously observed to lead to an increasing radiation Q [45]. However, in [45] only the energy stored outside the smallest sphere was considered in the case, where the ports were totally isolated. However, as presented in publication [P1], energy stored inside the smallest sphere plays the dominant role, and in practice, mutual coupling between the elements may be strong. Multiport loading schemes have been studied for example in the case of spiral and slot an-

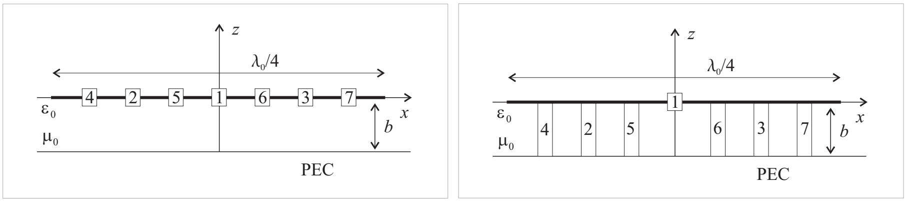

Figure 6: Multiple feeding (left) and loading (right) of a horizontal dipole over a conducting surface.

tennas in [46] and [47]. In these papers distributed loading was found to offer potential way to minimize the physical size of the antenna and control the input impedance of the antenna efficiently.

In publication [P4] the effect of multiple feeding and loading of a horizontal dipole over a ground plane was studied (see Fig. 6). In [P4] the inner energy as well as mutual coupling between the elements was included. By computational examples it was shown, that by feeding a dipole at multiple ports with suitable amplitudes, a slightly lower Q can be achieved than by feeding a similar dipole from a single port. Also, distributed loading of a similar element was analysed. According to a computational example, by tuning the element to resonance with suitable distributed shunt capacitors, notably lower Q values can be achieved compared to the case where the element is conjugately tuned with an inductor from a single port.

Thus, it can be concluded, that distributed feeding and loading provides a way to affect the inner fields created by the element. However, in realization challenges exist. In distributed feeding a complex network would be needed to match the feed lines and divide the power accurately between the ports. In distributed loading external wires would be needed to connect passive capacitors in the ports affecting the situation. On the other hand, capacitors could also be easilly realized with pieces of high-ε materials.

Part II

4 Platform insensitivity

The input impedance, radiation pattern and performance of small antennas are typically highly platform dependent. In modern applications, like RFID, the antenna may be attached directly on top of different kinds of objects and the platform effect becomes a performance spoiling feature. On the other hand, as discussed in the previous section, in some applications, like mobile phones, the effect of the platform can be exploited to enhance the antenna performance by controlled coupling. Still, also mobile phones suffer from the impedance and efficiency shifting effect in the vicinity of hand and head [48], [49]. To account for the impedance shifting effects of the platform, for example, adaptive varactor or MEMS tuning circuits have been proposed [50], [51]. However, these are complex and expensive systems and often not possible in low-cost applications like RFID.

The effects of the platform may be decreased by using a ground plane in the antenna structure to shield the element from the environment underneath. In addition to high reactive field level and low radiation resistance arising while operating in the vicinity of a conducting surface, there is also a challenge to minimize the size of the plane. For example, according to [52]–[54], a ground plane of wavelengths in size is needed to stabilize the input impedance of a vertical monopole. Also, results concerning circular microstrip antennas have been reported in [55]. The study shows that a ground plane radius beyond 1.3 times the patch radius is enough to stabilize the input impedance. A similar study concerning a PIFA structure has been reported in [56]. In the study the ground plane less than 0.2 λ in size had a major impact on the input impedance.

Platform insensitivity of the element may be understood by analysing the currents induced to the shielding ground. In publication [P5] the currents induced by vertical and horizontal point sources above an infinite perfect electric conductor were solved. In [P5] it was concluded that in addition to the height between the element and the ground plane, the induced surface currents were notably affected by the source orientation. The currents induced by vertical sources decayed proportionally to the inverse distance while the currents induced by horizontal sources decayed as the inverse distance squared. Thus, antennas with dominating horizontal current distribution concentrate the induced current to the smaller area and tend to be less sensitive to the platform as presented in the case of inverted-L antennas in Fig. 7.

However, dominating vertical current distribution is typical in many antenna structures designed to operate near a ground plane, like PIFA structures, since a vertical short tends to attract the current. In many applications, like mobile phones, this is an advantage, since induced current spreads to a wider area improv-

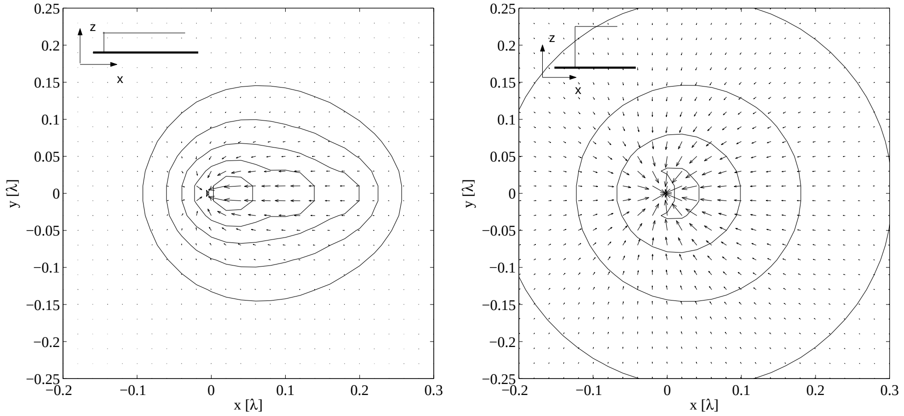

Figure 7: Surface current induced by flat (left) and high profile (right) inverted-L antenna.

ing the radiation performance of the antenna. However, if platform insensitivity is preferred, as presented in publication [P6], by widening the short of the PIFA element, i.e., reducing the inductance of the vertical part and lowering the height of the antenna, dominating horizontal current distribution and insensitivity to platform is achieved.

In addition to low profile PIFAs presented in [P6] and [P7], self-balanced structures like folded loops have been proposed as platform insensitive solutions (see e.g. [57], [58]) due to their concentrated ground current distribution. However, these antenna structures float above a ground plane, increasing the total thickness of the structure.

5 RFID and wireless sensors

5.1 Background

Lately, antennas for RFID and wireless sensor applications have gained growing interest in the research world and markets. In radio frequency identification (RFID) a reader device transmits a signal to the identification tags, in which the data is stored [59]. Thus, in a sense RFID can be understood to be similar to the bar code systems. However, the amount of data and reading ranges are much higher. Also, reading is possible without visual contact. Thus, RFID systems can be used to identify objects for example in logistics and industrial production or in key cards. Moreover, sensors can be attached to RFID platforms to allow the distributed monitoring of the environment [60], [61]. Thus, a plethora of applications exist for example in healt care, security and traffic.

Generally two kinds of RFID systems exist: near-field (HF) and far-field (UHF) RFID. In near-field systems, the wireless coupling is done through magnetic or electric field with inductors or capacitors as coupling elements and thus, the reading distances tend to be in the order of a few centimeters. On the other hand, in far-field RFID, electromagnetic coupling is utilized and the reading distances are several meters. In this thesis UHF RFID is considered.

In passive and semi-passive UHF RFID the systems operate with backscattering technique [59], [62]. Unlike in the conventional communication, the other part of the system, RFID tag, does not contain a transmitter, but the information is modulated to the backscattered signal (see. Fig 8). The identification tags contain the IC, possibly sensors and an antenna. In passive systems, the DC power needed for IC is generated from the incoming RF field with rectifier unit and no external power source exists making the lifetime of the tags limitless. However, the reading distances stay within a few meters, since only from 2W ERP (Europe) to 4W EIRP (N. America and Japan) is allocated for RFID readers. Thus, also the antenna performance and power transfer (impedance matching) to the IC become very critical features in succesfull system operation.

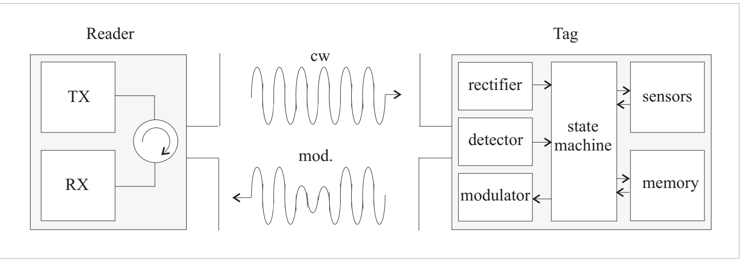

Figure 8: UHF-RFID system.

In semi-passive systems a battery supplies power to the IC. Still, the system works with backscattering technique lacking a transmitter in the tag. On the other hand, in active systems the tag contains a battery as well as a transmitter. Thus, for active systems the read ranges can extend up to hundreds of meters.

5.2 RFID antennas

As mentioned earlier, the electronics part of the tag is extremely small and in many cases, is embedded in the antenna substrate making the antenna the largest component. In other words, no fixed device chassis exist, but the antenna is directly attached to different objects or environments to be identified and monitored. Thus, small size and platform insensitivity are the main design characteristics of RFID antennas. Also, the antenna is matched directly to the reactive impedance of the IC, and thus, the antenna impedance is not real as in traditional antenna design cases. In addition, RFID tags are mass production items, and thus the material and manufacturing issues need to be considered in the antenna design process.

In order to make an RFID system insensitive to tags orientation, the majority of RFID readers are circularly polarized, however, the handedness of the polarization may vary. Thus, linear polarization of the tag is preferred to sustain operation in different orientations and with different readers.

The majority of the RFID tag antennas on the market today are two-dimensional structures, mainly printed dipoles (see Fig. 9 left [59]). Two-dimensional structures are small in size, inexpensive and suitable for mass production. In the literature many examples exist, e.g. [63], [64]. The desired input impedance of dipoles is achieved simply by making the antenna longer than the resonant length and asymmetrically feeding the antenna. Also, impedance transformers, like loops around the feed, may be utilized to gain the desired impedance. Dipoles may be shaped to many forms, even into the form of text [65]. In addition to dipoles, also slot structures have been proposed [66].

However, two-dimensional structures have a major drawback: as the antenna is attached to different objects or environments, operation starts to fail due to dramatic shifts in impedance and efficiency [67], [68]. As discussed in Chapter 4, an antenna structure containing a ground plane needs to be used to make the antenna platform insensitive and usable in different environments, especially on metal. In Fig. 9 right an example of platform insensitive PIFA antennas similar to [P6] are presented. After the publication of [P6] several platform insensitive antennas for RFID have appeared in the literature (e.g. [69]–[71]).

Currently, different frequency bands are allocated for UHF RFID use in Europe (866–868 MHz), North America (902–928 MHz) and Japan (950–956 MHz) [72].

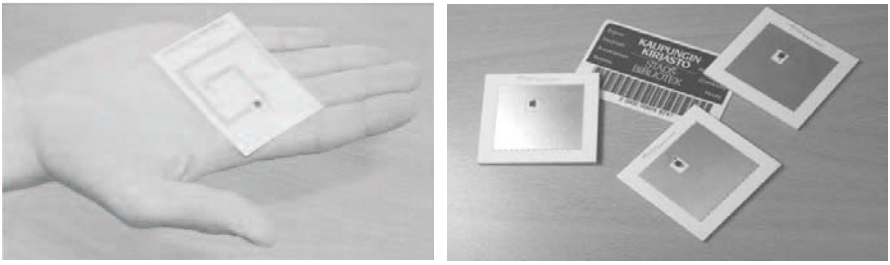

Figure 9: Printed RFID dipole (left) [59] and platform insensitive PIFAs (right) fed with RFID microchips.

Also 2.45 GHz and 5.8 GHz bands are available globally, but seldomly used because of the limited read range. Evidently, there is a demand for a universal tag containing a multi-band antenna. Fortunaly, unlike in mobile communication applications, the required operating bands are narrow, allowing the use of higher-Q antenna elements. On the other hand, low radiation resistance typically related to high-Q elements is a problem in practice due to low radiation efficiencies. However, this can be somewhat compensated by shaping the element as uniformly as possible to avoid ohmic losses and using low loss substrates.

As already mentioned in the antenna performance enhancement section, multiple resonances may be created to antennas by several elements or external circuit components. However, parasitic elements increase the antenna size and external components tend to be lossy. Also, in RFID antennas, external circuit components increase the cost of the tag, which in many cases is intolerable. Multi-band dipoles for RFID exploiting several resonator elements have been reported in the literature [73], [74].

In publication [P7], a dual-band antenna using an alternative approach is presented. In a PIFA structure, a floating port is utilized and the ground pin of

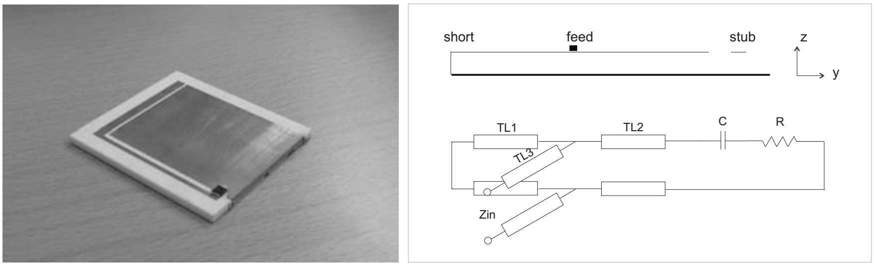

Figure 10: Dual-band, platform insensitive antenna (left) and an approximate circuit model (right).

the IC is connected to nominally a quarter-wavelength microstrip line to form a virtual ground (see. Fig. 10). In addition to the ease of manufacturing compared to vias, floating port offers a dual-band tuning possibility. In RFID, the desired input impedance of the antenna is usually strongly inductive and the resistance is low due to the direct matching to the capacitive IC. As presented in Fig. 10 right, a microstrip line acting as a virtual ground may be modeled as feed inductance ($TL3$), which can be used to move the impedance locus towards generator in the Smith chart. On the other hand, by bending the microstrip line towards the end of the patch element forms a series capacitance C, which controls the locus size. Thus, the antenna impedance can be led to pass the desired impedance level laying near the outer rim of the Smith chart twice leading to dual-band operation. Also, the current distribution of the antenna presented in [P7] is mostly horizontal, making the antenna platform insensitive.

5.3 Measurement techniques

Traditionally, antennas are verified with cable measurements. In this technique the antenna under test is connected to a network analyser, which measures the antenna impedance from reflection coefficients directly at the cable connection point (feed port), see Fig. 11. Similarly, radiation characteristics are verified by measuring transmission at different space angles between the antenna under test and a reference antenna. However, in the case of small antennas, the cable interferes with the radiated fields and affects the measurement results strongly. To minimize these effects, ferrite chokes can be used around the cable or the cable may be oriented at the angle where the field is the weakest.

However, in modern antenna applications like RFID, the antenna impedance is not real like the cable characteristic impedance leading to a huge mismatch and reflections at the connection point. Matching networks can be utilized between the antenna and the cable, but also the network platform itself may disturb the radiation. Thus, wireless measurement techniques are preferred to verify RFID antennas. Generally two kinds of measurements exist: backscattering and modulated backscattering measurements.

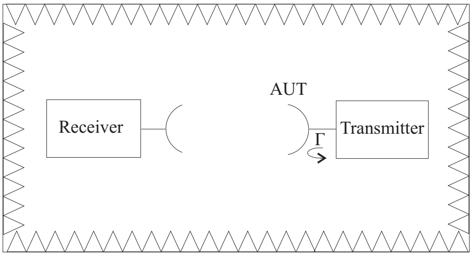

Figure 11: Measurement setup in a cable measurement.

5.3.1 Backscattering

In the backscattering the radar cross section (RCS) of the antenna is measured with different feed loads. The measurement setup of the backscattering method (also modulated backscattering) in presented in Fig. 12. In a simplified model, as the antenna is illuminated with RF power, antenna radiates back a portion of the power due to the impedance mismatch in the antenna feed. The RCS of such a system may be written as [75], [P8]

$$\sigma = \frac{4\pi A_e^2 |1-\Gamma|^2}{\lambda^2}, \tag{19}$$

where Γ is the reflection coefficient from antenna to the load resistance

$$\Gamma = \frac{Z_L - Z_A^*}{Z_L + Z_A}, \tag{20}$$

and A_e is the antenna effective aperture, which is related to the antenna gain G as

$$A_e = \frac{G\lambda^2}{4\pi}. \tag{21}$$

As presented in [76] the antenna under test and the transmitting and receiving antennas can be modeled as a linear three port network characterised by three impedance parameters. Thus, as presented in [77], [78], by measuring the antenna backscattering with three known loads information about antenna input impedance may be derived. After solving antenna input impedance, also the antenna gain can be calculated according to equations (19)–(21).

However, in practice limitations exist. In backscattering measurement, the method assumes the antenna radiation mode to be similar with all loads. In the case of simple antennas like dipoles, only one mode exists and the radiation pattern is similar in every case. However, if the antenna structure is more complex, different modes may be excited with different loads. Also, as the transmitted and backscattered signals are at the same frequency band backscattering measurement requires very low environmental interference and high resolution measurement equipment.

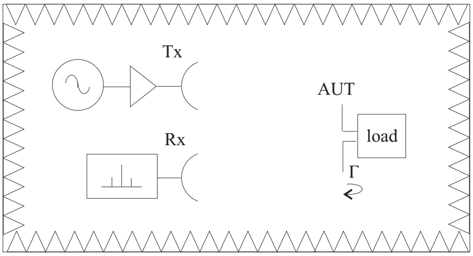

Figure 12: Measurement setup in backscattering methods.

5.3.2 Modulated backscattering

In the modulated backscattering the scattered signal from the antenna mode is transferred to the sidebands [P8]. Thus, the environmental reflections are reduced and less performance is needed from the measurement environment and equipment.

In the modulated backscattering an oscillator chip with a known input impedance is connected as a load to the antenna under test. As the oscillator drives the varactor at the input of the chip, the reactance of the chip varies modulating the phase of the current in the antenna circuit. The scattered field is thus phase modulated, which is seen as sidebands in the scattered signal. In the measurement, the transmitted power P_{tx} is increased until the IC chip gets enough power to wake up and the sidebands appear in the backscatter data. As the RF power P_{req} needed to start the modulation is known, the antenna gain G including the impedance mismatch $1-|\Gamma|^2$ can be calculated using the Friis equation

$$G(1-|\Gamma|^2) = \frac{P_{\mathrm{req}}}{G_{\mathrm{tx}}P_{\mathrm{tx}}}\left(\frac{4\pi r}{\lambda}\right)^2, \tag{22}$$

where G_{tx} is the transmitter gain and r the measurement distance. The drawback of the method is that the mismatch between the antenna and the load cannot be extracted from the results. Measuring the required transmit power as a function of the frequency gives information about the antenna bandwidth. Moreover, the radiation pattern of the antenna may be measured by recording the critical transmitted power P_{tx} as a function of space angles.

In publication [P8] the theory of the modulated backscattering as well as the accuracy of antenna gain and pattern measurements are discussed. Also, the harmfull effect of the measurement cable is demonstrated compared to the wireless measurement technique. Furthermore, modulated backscattering has been used in verifying the RFID antennas presented in publications [P6] and [P7].

6 Summary of publications

[P1] Power and Q of a horizontal dipole over a metamaterial coated conducting surface

The paper presents the power radiated by a conductor-backed horizontal dipole with different substrate material parameters. The radiation enhancement due to permeability, negative parameters and more importantly, near-zero permittivity is discussed. Also, a notable decrease in the quality factor with near-zero permittivity substrates in a dispersionless case is reported. In addition, the dominating role of the internal stored energy is showed compared to the energy stored outside the smallest sphere enclosing the element.

[P2] Near-zero permittivity substrates for horizontal antennas: Performance enhancement and limitations

The paper continues the work published in [P1]. In the paper, the role of dispersion and size of a near-zero permittivity substrate is discussed. The paper concludes, that the power enhancement achieved with near-zero permittivity is greatly affected by the size of the substrate. Also, the dispersion is found to increase the stored energy leading in higher quality factors than estimated in publication [P1]. However, it is reported that already half-wavelength times half-wavelength size substrate leads to remarkably lower quality factors even while including the material dispersion compared to the air-filling case.

[P3] Bandwidth limitations of dipoles matched with non-Foster impedances

The paper presents new results concerning the negative-reactance matching. First, a new equivalent circuit model for small dipoles is proposed. The model includes a circuit model for TM_1 field derived by Chu and a network modeling the fields stored inside the smallest sphere enclosing the antenna. In the paper it is concluded that the internal fields limit the bands achieved with non-Foster components. However, drastic bandwidth improvements are reported while tuning small dipoles with two non-Foster components. Also, the component tolerance issues are discussed.

[P4] Impedance and quality factor of mutually coupled multi-port antennas

The paper presents results gained by feeding and loading a horizontal dipole over a conducting surface at multiple input ports. It is concluded, that by multi-port feeding slightly lower quality factors are possible compared to the single-port case. Moreover, a notable decrease in the quality factor is reported while loading the antenna with shunt capacitors.

[P5] Decay of ground plane currents of small antenna elements

In the paper the ground plane currents induced by horizontal and vertical point sources are derived. It is reported that currents induced by horizontal point sources above a ground decay more rapidly compared to the vertical sources leading to less platform sensitive behaviour.

[P6] Planar inverted-F antenna for radio frequency identification

A novel PIFA structure for RFID is proposed having platform insensitive characteristics due to dominating horizontal current distribution.

[P7] Dual-band platform tolerant antennas for radio-frequency identification

The paper presents a new PIFA structure for RFID showing dual-band and platform insensitive operation. A novel dual-band tuning technique exploiting the reactive matching level and floating port is presented.

[P8] Antenna effective aperture measurement with backscattering modulation

In the paper a novel wireless measurement technique for verifying RFID antennas is presented. In the measurements a test chip, with known characteristics, is attached to the antenna feed and the antenna gain including the impedance mismatch and pattern may be measured using a modulated backscatterign signal. In the example measurements also the hazardous effect of the measurement cable is indicated compared to the wireless technique.

7 Conclusions

In this thesis, theory and solutions for problems related to small antennas are discussed. Small antennas, and especially antennas operating close to a conducting surface, tend to have high reactive field level and low radiation resistance leading to high radiation quality factor. In reality, this leads to narrowband operation and low radiation efficiency.

Performance limitations of small antennas are typically studied while taking only into account the fields associated with spherical multipole modes outside the smallest sphere enclosing the antenna and assuming the internal fields zero. However, in practice, the energy stored in the reactive internal fields is dominating compared to the fields outside the sphere, and is, in fact, the performance limiting feature. Thus, in this thesis, the separation between these two antenna regions and the importance of the internal fields are emphasized.

In the first part of the thesis, alternative approaches to overcome the small antenna problem by affecting the antenna inner fields have been analysed. First, it has been concluded that with certain material loadings, permeability, negative-parameter materials and, more importantly, near-zero permittivity, the radiation resistance and radiated power of a horizontal antenna above a ground plane may be increased notably. However, in practice near-zero permittivity is implemented with dispersive structures, which increase the stored energy and lead to higher radiation quality factor. Also, the finite size of the substrate limits the achievable increase in radiation resistance. Moreover, the realization of near-zero permittivity materials, especially as compact structures, is challenging and expensive.

Another way to improve the antenna performance is to use non-Foster (negative reactance) components to cancel some reactive energy from the antenna impedance. In this thesis a new equivalent circuit for a small dipole element, which makes a separation between the fields inside and outside the smallest sphere enclosing the antenna, is derived. By exploiting this equivalent circuit, it was concluded that the internal stored energy of the antenna limited the achievable bandwidths. Still, while tuning even very small dipoles with two negative components, drastic bandwidth enhancements could be achieved. However, with very small antennas, the active component tolerances get strict limiting the realization possibilities of the system. All in all, as non-Foster tuning contains active components and complex circuitry, it is suitable only for high-end products.

Yet another approach to the small antenna problem is multi-port feeding and loading technique. With both methods, antenna inner fields could be slightly affected in a favourable way leading to enhanced antenna performance. Being passive and simple method, multi-port feeding and loading could find potential also in low-end bulk products.

In the second part of this thesis small antennas for RFID and wireless sensors are discussed. For these antennas, several characteristic design features exist. For example, the impedance of the RFID antenna is directly matched to the reactive input impedance of the IC. Also, RFID tags are mass production devices, and material and manufacturing issues play a key role. More importantly, RFID antennas are directly attached on different objects and environments and thus, platform insensitive behaviour is needed. Thus, in this thesis a theory and implementation methods for platform insensitive antennas are proposed. Also, a few antenna designs showing platform tolerant characteristics and direct impedance matching to the IC are introduced. Also, an easy dual-band tuning technique is presented. In addition, a new wireless measurement method is presented for verifying RFID antennas.

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Abstract

The focus of this thesis is on the performance enhancement of small antennas and design and verification of antennas for radio frequency identification (RFID) and wireless sensors. The work is presented in eight scientific papers and in a summary, which introduces relevant fundamental concepts and previous work done in the field of small antennas.

Previously, several performance enhancement methods have been proposed to improve the antenna performance especially in mobile communication applications. However, solutions for the fundamental small antenna problem, high reactive energy and low radiation resistance, which in practice lead to narrowband and low efficiency operation, are rarely provided. In this thesis, alternative methods to alleviate the high reactive energy and low radiation resistance like material loading, non-Foster tuning and multi-port loading are discussed.

Also, lately antennas for RFID and wireless sensor applications have gained growing interest. However, several characteristic design features exist for these antennas. Especially, the concept of platform insensitivity is essential and discussed in detail. Also, antenna designs and dual-band tuning technique applicable to RFID antennas are presented. In addition, wireless measurement techniques for RFID antenna verification are reported.

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Nimeke

Pienten antennien suorituskyvyn parantaminen sekä sovelluksia etälukuun

Tiivistelmä

Väitöskirjatyö käsittelee pienten antennien suorituskyvyn parantamista sekä etälukuun (RFID) ja langattomiin antureihin soveltuvien antennien suunnittelua ja mittausta. Työ koostuu kahdeksasta tieteellisestä julkaisusta sekä yhteenvedosta, jossa on esitetty pienten antennien peruskäsitteitä sekä alan aikaisempia tutkimustuloksia.

Aikaisemmin pienten antennien suorituskykyä on pyritty parantamaan mm. matkaviestinlaitteissa. Kuitenkin ratkaisuja pienten antennien perusongelmaan, korkeaan reaktiiviseen energiatasoon sekä matalaan säteilyresistanssiin, jotka tekevät antennista käytännössä kapeakaistaisen ja hyötysuhteeltaan huonon, on harvemmin esitetty. Tässä työssä on analysoitu eri menetelmiä korkean energiatason ja matalan säteilyresistanssin lieventämiseen, kuten materiaalikuormitusta, non-Foster-viritystä sekä usean portin kuormitusta.

Viime aikoina etälukuun ja langattomiin antureihin soveltuvat antennit ovat herättäneet kasvavaa kiinnostusta. Näissä sovelluksissa antenneihin liittyy kuitenkin useita erityisiä ominaisuuksia. Erityisesti antennien alustaepäherkkyys on tärkeää, ja sitä on käsitelty työssä yksityiskohtaisesti. Lisäksi tässä työssä on esitetty RFID-antennimalleja sekä niihin sopiva kaksitaajuusviritystekniikka. Myös RFID-antenneille soveltuvia langattomia mittaustekniikoita on esitetty.

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