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Sami Myllymäki

CAPACITIVE ANTENNA SENSOR FOR USER PROXIMITY RECOGNITION

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF TECHNOLOGY,
DEPARTMENT OF ELECTRICAL ENGINEERING

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SAMI MYLLYMÄKI

CAPACITIVE ANTENNA SENSOR FOR USER PROXIMITY RECOGNITION

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Supervised by
Professor Heli Jantunen

Reviewed by
Professor Matthias Hein
Doctor Anatoli Deleniv

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Abstract

Users of mobile devices induce detrimental electrical effects on the antenna when devices are operated in close proximity to either the head, hand or fingers. A totally covered antenna can suffer over 10 dB gain loss and force an increase in the output power of the device, which additionally causes shorter battery life and higher emissions in terms of the specific absorption rate (SAR) and hearing aid compatibility (HAC).

The user effect can be minimized with compensation methods such as active antenna tuning or a spatial antenna selection. In this thesis, capacitive proximity sensors are investigated in order to provide new characteristics for user effect compensation.

The thesis has three parts. In the first, hand positions along the device chassis are measured with the antenna integrated capacitive sensor. The results are in proportion to the induced hand loss in the antenna. Secondly, discrete electrode sensors are studied as hand and single finger proximity recognition and are found to have a good performance in applications. Thirdly, weaknesses of integrated and discrete sensors are evaluated. The discrete sensor had an induced low antenna loss of 0.05–0.20 dB in the 1–2 GHz bands. In contrast, the integrated sensor caused radio interference in proper GSM channels, decreasing the sensitivity of the radio receiver.

The capacitive sensor is able to sense the user proximity effect regardless of antenna matching, which may be changed in a complex manner when more than one electrical resonance is used in the same frequency band or when the matching is modified mainly by the resistive component. In multiple-antenna applications, capacitive sensors are able to maintain up-dated information of user loads of all antennas.

Combining the results, the discrete electrode sensors fulfilled the technical and operational objectives of this thesis. They are able to detect a single finger or other user objects, they have low losses and they can be located in such a way that will not consume extra room in mobile devices.

Keywords: antenna, capacitive proximity sensor, mobile device, user effect

Myllymäki, Sami, Kapasitiivinen antennin läheisyysanturi käyttäjän läheisyyden ilmaisuun.

Oulun yliopiston tutkijakoulu; Oulun yliopisto, Teknillinen tiedekunta, Sähkötekniikan osasto,
PL 4500, 90014 Oulun yliopisto

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Tiivistelmä

Kannettavien päätelaitteiden käyttäjät aiheuttavat sähköisiä häviöita laitteen antennissa kun laitetta käytetään käden, pään tai sormien läheisyydessä. Kokonaan peitetyn antennin häviö voi olla yli 10 dB, mikä johtaa laitteessa lisääntyneeseen tehontarpeeseen, lyhyempään pariston kestoon ja korkeampiin haitta-arvoihin SAR ja HAC mittauksissa.

Käyttäjän vaikutusta voidaan minimoida kompensaatiotekniikoilla kuten antennin säädöllä ja -valinnalla. Tässä työssä kapasitiivisia antureita tutkittiin uusien käyttäjävaikutuksen kompensaatiotekniikoiden löytämiseksi.

Työ jakaantuu kolmeen osaan. Ensimmäiseksi käden sijainti laitteen rungon suhteen on mitattu kapasitiivisella anturilla. Nämä tulokset ovat verrannollisia käden aiheuttamaan kuormaan antennissa. Toiseksi erillisiä antureita tutkittiin käden ja sormien havaitsemiseksi hyvällä menestyksellä eri sovelluksissa. Kolmanneksi arvioitiin antennin integroidun ja erillisen anturin heikkouksia. Erillisen anturin aiheuttama häviö antenniin oli 0.05–0.20 dB 1–2 GHz taajuuskaistalla. Vastaavasti integroitu anturi aiheutti radiohäiriöitä tietyillä radiokanavilla, mikä heikentää vastaanottimen herkkyyttä.

Kapasitiivinen anturi havaitsee käyttäjän läheisyyden riippumatta antennin sovituksesta. Sovitus voi muuttua monimutkaisesti kun useampaa sähköistä resonanssia käytetään samalla taajuuskaistalla tai sovitukseen vaikuttaa sähköisesti resistiivinen kuorma. Moniantennirakenteissa kapasitiiviset anturit voivat tuottaa jatkuvaa informaatiota käyttäjän aiheuttamasta kuormasta eri antenneissa.

Erilliset kapasitiiviset anturit täyttivät ne tekniset ja toiminnalliset vaatimukset, jotka työlle aluksi asetettiin. Niillä voidaan havaita yksittäinen sormi tai muu kohde, ne ovat pienihäviöisiä, ja ne voidaan sijoittaa tilaa säästävällä tavalla nykyisiin päätelaitteisiin.

Asiasanat: antenni, kannattava päätelaite, kapasitiivinen läheisyysanturi, käyttäjävaikutus

To my Family

Acknowledgements

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I am thankful to my supervisor professor Heli Jantunen for giving me this opportunity and the support to perform this research. In addition, professor emeritus Seppo Leppävuori, professor Eero Ristolainen†, and the personnel who worked in the AATE-project and the staff of the Microelectronics and Materials Physics Laboratories are acknowledged.

My research career has been financially supported by the Infotech Oulu Graduate School, the Nokia foundation, the Seppo Säynäjäkangas foundation, the Finnish Foundation of Electrical Engineers, the Tauno Tönning foundation, the Riitta and Jorma J. Takanen foundation and the Eemil Aaltonen foundation that all are acknowledged for supporting the work.

List of Abbreviations and Symbols

BST	Barium Strontium Titanate
CIE	Coupled Integral Equations
CCE	Capacitive Coupling Element
CTIA	Cellular Telecommunications & Internet Association
DAM	Dynamic Antenna Matching
DUT	Device Under Test
EEM	Eigen-function Expansion Method
EM	Electro Magnetic
EMC	Electro Magnetic Compatibility
FDTD	Finite-Difference Time-Domain
GaAs	Gallium Arsenide
GSM	Global System for Mobile communications
HBM	Human Body Model
MEMS	Micro Electro Mechanical System
MIMO	Multi Input Multi Output
MoM	Method of Moment
PCB	Printed Circuit Board
PIFA	Planar Inverted F-Antenna
PIN	Positive-Intrinsic-Negative
PDMS	PolyDiMethylSiloxane
SNR	Signal to Noise Ratio
SP4T	Single-Pole Four-Throw
TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power
TRX	Transceiver
UHF	Ultra High Frequency
RF	Radio Frequency
C_{in}	input capacitance
C_p	parasitic capacitance

List of original papers

Original papers are referred to throughout the text by their roman numbers.

I Myllymäki S, Huttunen A, Berg M, Komulainen M & Jantunen H (2009) Method for measuring user-induced load on mobile terminal antenna. Electronics Letters 45(21): 1065–1066.

II Myllymäki S, Huttunen A, Palukuru VK, Jantunen H, Berg M & Salonen ET (2010) Capacitive recognition of the user`s hand grip position in mobile handsets. Progress In Electromagnetics Research B 22: 203–220.

III Myllymäki S, Valkonen R, Holopainen J, Huttunen A, Palukuru VK, Berg M, Jantunen H & Salonen ET (2011) Capacitive-Sensor-Induced Losses in 900-, 1800-, and 1900-MHz Antennas. IEEE Antennas and Wireless Propagation Letters 10(1): 330–333.

IV Myllymäki S, Huttunen A, Jantunen H, Berg M & Salonen ET (2011) Measurement method for sensitivity analysis of proximity sensor and sensor antenna integration in a handheld device. Progress In Electromagnetics Research C 20: 255–268.

V Myllymäki S, Huttunen A, Palukuru, VK, Jantunen H, Berg M & Salonen ET (2011) Feasibility study of antenna integrated capacitive sensor in operational mobile phone. Progress In Electromagnetics Research C 23: 219–231.

Paper I discusses the user hand induced effect on the antenna as measured when the hand position was moved along the phone chassis. The effect was measured in terms of the matching, absorption loss and the low frequency capacitive load of the dual band GSM antenna. As a result of Paper I, the full hand proximity effect of the antenna can be evaluated by measuring the antenna capacitance but not by measuring only the matching.

Paper II considers the hand position recognition measurements by using discrete measurement electrodes on the PCB of the phone. The bottom end of the phone was found to be the optimal position for proximity sensors when the whole hand is going to be sensed. The antenna was found to diminish the coverage of the discrete sensor when located behind the radiation element.

Paper III presents the measurement results of antenna induced losses caused by the discrete proximity sensors. 5 mm^2 capacitive electrodes realized loss < 0.2 dB, which is similar in size to the loss induced by currently used matching sensors.

Paper IV concentrates on the recognition of the finger position, especially in close proximity to the antenna element. Utilizing the sensor sensitivity measurement method, the paper presents some optimal discrete sensor locations besides the antenna element. As a result, the radiation element needs at least two discrete sensors in order to cover all possible finger proximity directions while maintaining low antenna induced sensor loss.

Paper V presents the investigation of the antenna sensor integration evaluated from the radio device point of view. As a result, the sensor signal induced interference that reduced the receiver`s sensitivity in certain channels. This behaviour limits the usability of the antenna sensor integration.

The main work contribution to Papers I-V is from the author. All papers were primarily prepared by the author. A. Huttunen as co-author in all papers was responsible for support operations within the electronics and computer software used in measurements, whereas the author was responsible for measurement setups, methods and most of the practical measurements. R. Valkonen as co-author in Paper III was the antenna designer and the author was the sensor designer in the collaborative research. Prototype manufacturing and measurements were mainly arranged at the University of Oulu by the author, except for the active antenna measurements, which were performed at the research partners` measurement laboratories.

Table of Contents

1 Introduction

This chapter presents objectives and the outline of this thesis. A literature survey is divided into three parts. The first part introduces the antenna`s electrical performance in terms of the vicinity of the user`s head and hand, the second part introduces compensation methods to minimize deterioration of the antenna`s performance, and third part presents existing capacitive sensors used for user proximity detection.

1.1 Objective and outline of this thesis

The first objective of this thesis was to design and incorporate a capacitive sensor into a mobile phone in order to detect the human user’s proximity and relate it to the corresponding electrical effect in the antenna. The objective can be divided into operational and technical objectives. Operational objectives are the detection of the whole hand and the detection of a single finger. Technical objectives include the antenna sensor implementation and measurements of sensor characteristics. The antenna sensor implementation is further divided into antenna integrated sensor and discrete electrode sensor topics.

The novel antenna sensor structures introduced were designed and optimized utilizing active and passive antenna measurements (Satimo Starlab, Satimo Stargate), antenna matching measurements (Network analyser) and laboratory made sensor measurement arrangements. The studied antenna sensor devices were fabricated using traditional PCB (printed circuit board) techniques and sensor systems were implemented in commercial mobile phones.

Chapter one is based on a literature survey describing the state-of-art of antenna effects and capacitive sensors in the field. Chapter two presents measurements methods and prototypes, which are used in the experimental measurements presented in chapter three. The sensitivity and usability of the antenna integrated sensor are investigated. The capacitive sensors, used as single or two electrode discrete sensors for single finger or whole hand recognition in close proximity to the antenna, are also studied. The sensitivity of the sensor is measured in various mechanical circumstances. The measurement of antenna gain reduction and interference effects in the RF (Radio Frequency) receiver are reported in chapter four. Finally the conclusive picture emphasizing the best solutions for antenna proximity sensors are presented.

1.2 Antenna performance in the vicinity of head and hand

The use of a mobile phone in close proximity to the human head and hand causes the phone`s electromagnetic coupling at radio frequency to pass through human tissues. This effect decreases the performance of the antenna by changing its operation frequency, the input impedance, the current distribution, the radiation pattern and the radiation efficiency [1–8].

The antenna to head/hand interactions have previously been studied by using numerical methods such as the Method of Moment (MoM), Coupled integral equations (CIE) [1], the Finite-Difference Time-Domain (FDTD) [2], and the Eigen-function Expansion Method (EEM) [3]. Among these methods, the FDTD method has been widely used because of its ability to handle the complex geometry of antennas and the nearby human tissues.

Electromagnetic (EM) coupling of the PIFA (Planar Inverted F-Antenna) structure to a homogenous spherical head model has been investigated in the 900 and 1800 MHz bands by using the CIE/MoM simulation approach [1]. The peak gain in the direction of the head decreased as much as 7 dB and 5 dB at 900 and 1800 MHz frequencies, respectively. Additionally, research utilizing the FDTD method [2] discovered that the grip style influences the communication performance. For example, the large hand (adult) induced antenna gain deterioration effect was more detrimental by 2 dB at 900 MHz and 1.5 dB at 1800 MHz than the corresponding effect with a small hand (child).

The effect of the user’s hands on the performance of 900 MHz antennas in handheld terminals was studied in terms of the input impedance, efficiency, and far-field directional pattern of the internal capacitive coupled element antenna in the lower UHF (ultra high frequency) band [4]. The study was carried out by applying FDTD simulations and comparing them to the active antenna measurements. In the worst case, a hand induced deterioration of 7–11 dB in the antenna efficiency was measured compared to the free space results. The power absorption by the hand (3.5 dB radiation loss) is a more severe problem for the total efficiency than the change of the matching (1.9 dB matching loss).

The influence of the user effect on antenna impedance variation was studied in [6] and the effects of bone and muscle were compared. The fundamental impedance of the antenna became more resistive and inductive as the level of user load increased. Additionally there was a sharp increase in the level of impedance mismatch when a part of the finger was placed directly above part of the antenna. The mismatch that occurred when a single finger was on the antenna was similar to that when the entire antenna was covered. 2–4 dB deterioration at 900 MHz was found. Corresponding results measured from PIFAs are presented in [7] highlighting the detrimental effect of finger positions over the antenna.

The average body loss due to the user's head was measured to be 1.6 dB and additional body loss due to the user's hand was 2.6 dB [10]. The human body's loss effect on a triple-resonance PIFA type antenna was determined in [11] by measuring and analyzing the impedance mismatch and absorption losses caused by the head and hand with six different hand grips. In the calling mode, head and hand total loss was measured to be 3.9–8.0 dB at 900 MHz (for matching loss 0.6–4.5 dB) and 1.4–9.5 dB at 1800 MHz (for matching loss 0.6–2.0 dB) with different hand positions. The impedance mismatch was found to have a minor contribution to the total loss.

For PIFA antennas, an absorption loss of 14 dB and mismatch loss of 0–4 dB at 900 MHz, and an absorption loss of 6–11 dB and mismatch loss of 0–3 dB at 1800 MHz were measured [12]. At all frequencies the absorption loss was much larger than the mismatch loss. Corresponding results are also presented in [13, 14] .

Several one or two hands models and configurations in handheld usage have been investigated in [8] by using the FDTD method with PIFA and monopole antennas. The human hand was found to be the main cause of absorption and mismatch losses in antennas. The absorption loss was several decibels higher than the mismatch loss. An investigation of mobile-phone grip styles over a sample population of 100 people was arranged concerning the "shell" and the "bar" phone next to the user's head. The positions of the hand and fingers were varied for both phones investigated. Grip styles in "receive" and "call" modalities were highly correlated among the people and the size of the mobile phone was the main influencing factor in the users' grip style. In the data mode, people usually used both hands. When a single hand was used in the data mode, users kept the same grip style and position for a long time. The positions of pointing fingers changed almost at each key stroke.

Antenna research directed towards lower user effect sensitivity was performed in [5]. An antenna was designed in order to minimize the reduction in user induced efficiency at 900 MHz GSM (Global System for Mobile communications) operation. The applied antenna was called the EMC (Electromagnetic compatibility) internal GSM dual-band antenna embedded in the mobile phone.

The equivalent circuit model was used to explain the impedance and efficiency behaviour of a capacitive coupling element antenna and PIFA with the user’s body effect [9]. The model gives solutions to try to place the antenna element in such a location that the user’s body does not cause high loading, or to match the antenna over an impedance bandwidth so that the detuning does not result in high degradation of the matching efficiency. The model gives a good basis for adaptive antenna matching.

According to the literature review, antenna loaded conditions can be divided into four basic cases presented in Fig. 1: The hand`s position along the phone chassis (a), the phone`s position in terms of the head (b), the finger`s position in terms of the antenna (c) and the hand's position on the phone in the web browsing mode (d). The human user induced deterioration effect is high at the calling mode. The web browsing mode is not widely studied and its standardizing is incomplete. Due to heterogeneous types of devices, methods of browsing techniques can vary depending on the device used like smart phones, tablets etc. Additionally antenna development does not always follow the speed of device development. Thus there is a need for technical solutions that help with antenna performance requirements. A certain solution could be the antenna proximity sensor.

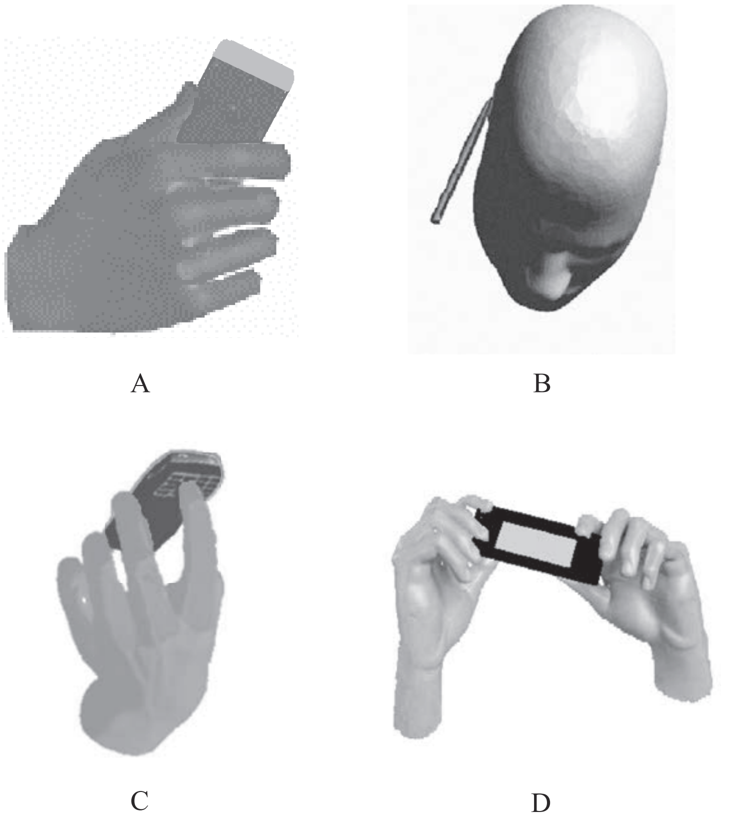

Fig. 1. Total efficiency of antenna used in mobile devices is decreased by (A) user`s hand position along chassis, (B) user`s head, (C) user`s index finger position in calling mode and (D) finger locations in web browsing mode.

1.3 Compensation methods for antenna loading

The user induced effect on antenna matching can be compensated by using antenna matching tuners, whose purpose is actively to change antenna matching components and thus restore the original matching conditions. However, the absorption part of the effect cannot be compensated with the matching tuner technique. [15–17, 19]

Matching tuner implementations involve different techniques e.g. tunable semiconductive varactors and a coil connected as a π-network matching circuit [15]. The principle of the system is presented in Fig. 2a. The transmitted input power to the antenna can be increased by about 2–3 compared with the fixed capacitance matching system. More advanced adaptive matching tuning methods for the π-network are presented in [19]. The antenna reflected power is measured with the coupler presented in Fig. 2b. The circuit is able to detect the change in the reflection coefficient in the antenna and re-tune the antenna matching. The matching control presented in Fig. 2b was realized with a fixed bank of capacitors (1.5, 3.9, 6.8, and 15 pF) connected to the PIN (Positive-Intrinsic-Negative) diode switches (390 MHz SQM1150 of TEKELEK) [16].

A corresponding antenna matching system utilizing MEMS (Micro Electro Mechanical System) switches is presented in Fig 2c. The operation frequency is 10–20 GHz and the re-configurability is achieved by using open-circuited stubs and a bank of MEMS switches. The system utilizes a four bit tuner covering sufficient matching accuracy in the application and it can be implemented onto a silicon substrate. [17]

Fig 2d presents a dual band GSM PIFA antenna tuning system utilizing GaAs technology based semiconductor SP4T switches. The system provided an antenna gain improvement of 2–4 dB at 900 MHz GSM band and 2 dB at 1800 MHz GSM band. [14]

The main drawback with currently used matching sensors is the inability to sense the human induced absorption loss in antennas. The absorption loss is dominating loss mechanism compared with the matching loss. In addition, there are other optional technologies to improve the tunability of microwave devices: semiconductor, magnetic, ferroelectric, liquid crystal, optical and mechanic technologies [18]. They can be compared in terms of power consumption, bias voltage, speed and a quality factor. Ferroelectrics have low power consumption, but need high bias voltage. Semiconductors have low bias voltages, but quality factors are low. Magnetic and mechanical (MEMS, piezo transducers) technologies have high quality factors but they are rather slow in operation. Unfortunately new technologies usually suffer in terms of reliability, costs and integration.

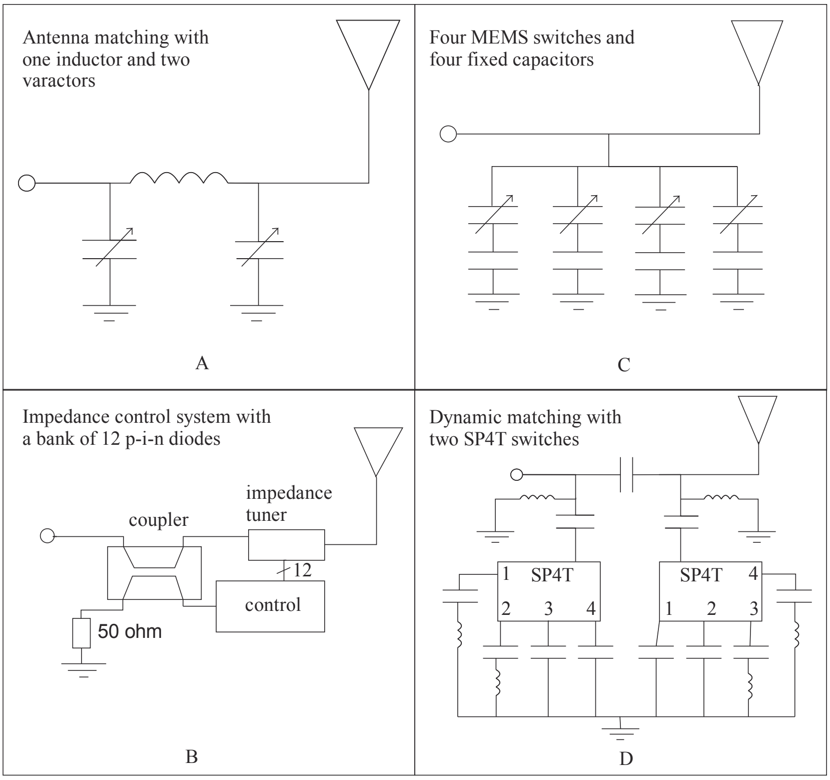

Fig. 2. (A) Simple π-network impedance matching circuit for antenna matching, (B) antenna reflection coefficient measurement and impedance matching with bank of capacitors, (C) MEMS switch operated bank of open stubs and (D) commercial switch circuit operated matching circuit.

1.4 Capacitive sensors

Capacitive sensors are widely used in the automation and robot industries as proximity sensors. The capacitive sensing method is also used in touch screens of handheld devices. The principle of operation is that the electric field changes in terms of the proximity of a dielectric or metal object.

Capacitive proximity sensors are used in human safety applications in e.g. chainsaws (10 cm distance) and pneumatic devices [20, 22], robot hand applications (0–8 cm distance) [21] and for seat occupancy sensing in cars [23]. Typical operating frequencies are 80 kHz, 250 kHz and 500 kHz. Multilayer liquid crystal film is used as a proximity sensor in chemical and biological sensing applications [24]. Conductive polymers and metallic fibres integrated into fibre-meshed structures are used as textile built capacitive sensors [25].

A typical capacitive proximity sensor widely used in the process industry is presented in Fig. 3a. The range of the probe changes as a function of the size of the sensing area. The maximum distance at which a probe is useful is approximately 30–40% of the sensor's diameter. Fig. 3b presents the structure of a dual-mode sensor consisting of a 16x16 array of unit cells [21]. A cell is composed of five Polydimethylsiloxane (PDMS) layers with copper electrodes embedded. Two electrodes (top and bottom electrodes) form a capacitor for tactile sensing, separated by air and by an insulation layer. The initial capacitance of a cell has been estimated as 171 fF at 250 kHz frequency, with the relative permittivity of PDMS of 2.75. When a contact pressure is applied to a bump, the upper PDMS layer deforms and capacitance increases until the air gap is completely closed. A typical application is flexible touch screens.

The proximity sensor utilizing transmission circuit incorporated an 80 kHz Wien bridge oscillator and a single low-power operational amplifier (Fig. 3c). The frequency of operation was chosen in order to maximize the system sensitivity, by means of a rectified mean value detector, after active filter stages for reducing disturbances and hence the probability of false alarms [20].

The sensor of a three elements system is shown in Fig. 3d [23]. It has a transmitter element and a receiver element consisting of a receiver segment and a receiver coil. The receiver segment serves for capacitive sensing, whereas the receiving coil is magnetically linked to the transmitter element, providing the ability to distinguish the human body from a metal object.

Capacitive proximity sensors can be provided with a shielding function, which excludes the parasitic terms from the results. In this technique, a copy of the measurement signal is fed to unwanted objects such as the ground plane of the device. After that the copied response is subtracted from the proper measurement response and the ground plane effect can be excluded. [22]

The applicability of capacitive sensors to the antenna applications has electrical and mechanical criterions. They are used for human proximity sensing in various devices including portable devices. The sensing method in Fig. 3c could be straightforwardly utilized in this application. Physical sizes of sensors presented in Fig. 3a and 3d should be decreased and integrated into smaller devices. The inductive sensor presented in 3d is not necessarily needed. The sensor solution in Fig. 3b presents the size scale (1 mm) and technical performance (sensing distance several cm) of desired scale when comparing it with requirements of current application.

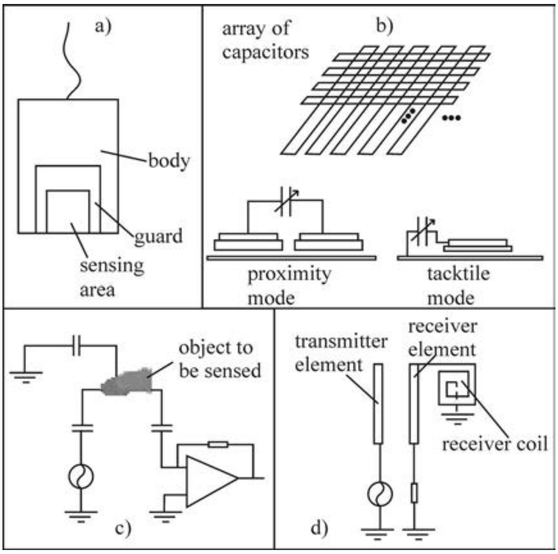

Fig. 3. (A) Capacitive proximity sensor used in process industry, (B) µm scale polymer film based tactile / proximity sensor for touch applications, (C) amplifier circuit with proper filtering stages and (D) sensor system including capacitive and inductive elements.

2 Experimental methods

The scope of the chapter is focused on presenting used measurement methods as well as sources of antennas utilized throughout the study.

2.1 Passive antenna measurements

Passive antenna measurements used in Papers I-III and V were performed in a Satimo Starlab (a chamber of 2 m x 2 m x 1 m) antenna measurement system in the University of Oulu. The system operates a multi-probe measurement technology with a wide band (from 0.8 to 18 GHz) probe array composed of a number of evenly spaced elements placed around the circumference of the support structure. The maximum allowed antenna diameter is 45 cm. A device under test (DUT) is placed at the centre of the support structure and measurements are made by electronically scanning the array (15 probes) in elevation and by rotating the DUT 180° in azimuth. For passive measurements the chamber is interfaced to a vector network analyzer and a computer. Antenna characteristics such as gain and total efficiency can be calculated at every frequency point in the desired frequency band. A full 3D graphic output representing the antenna performance can be executed from the results. Passive antenna measurements used in the thesis were performed by the author, but corresponding measurements were also made by research partners in [4, 9, 11, 26].

Passive antenna measurements with operating proximity sensing system were performed in Satimo Starlab. However, the capability of the sensor was not measured during the antenna measurements. The sensor electronics was installed into backside of the PCB (40 mm x 110 mm) and initialized for sensing state before installing the device into the chamber. The sensor system was battery operated and shielded in order to avoid EMC problems. Contacts were created through vias on the PCB.

2.2 Active antenna measurements

Active antenna measurements used in Paper V were performed in Satimo Stargate antenna measurement chambers in collaboration with Nokia Oyj and Pulse Finland Oy. Total Radiated Power (TRP) and Total Isotropic Sensitivity (TIS) are industry standard methods for determining the authentic RF performance of wireless devices. They represent traceable quantitative metrics that completely represent the RF performance of a wireless device at the physical level including the antenna, the equipment under test (phone), and the effect of objects typically found in the near field of the device. TRP and TIS can quantify the “Over-the-Air” performance with a single value. In addition, the measurement procedure is standardized in the Cellular Telecommunications & Internet Association (CTIA) - controlled documentation [27].

The TRP is defined as the integral of the transmitted radiation intensity over the far-field sphere of the antenna. TRP can be measured after setting the phone at its maximum available power, which for GSM900 system is 2W (33 dBm) and for GSM1800/1900 1W (30 dBm). In addition to transmission losses inside the phone, hand and head can decrease TRP results 2 dB at 900/1800MHz frequencies [44]. In addition, the capacitive sensor can decrease TRP values. TRP specifications of 23 dBm for GSM900 and 24/24.5 dBm GSM1800/1900 are used by network operators.

The TIS is defined as the absolute received power level of the phone at the bit error ratio (BER) limit (< 2.4%) in known reference position (in chamber). TIS includes the signal transmission factor of the chamber in the reference position and the total efficiency of the mobile phone antenna, average transmission losses inside the phone and cable losses. In addition, the total efficiency includes effects of impedance mismatch relative to 50 ohm and losses in the near-in environment such as a head phantom. Reasons for poor sensitivity on a single channel or a small number of channels can be receiver in-band noise and spurious signals from the transmitter of the device being radiated back into the receiver. TIS specifications of -100 dBm at GSM900 and -101 dBm at GSM1800/1900 are used by network operators. Theoretical value for maximum conducted sensitivity is -109 dBm at GSM900/1800/1900 frequency bands.

In this thesis TRPs and TISs were measured at two GSM bands 900 / 1900 MHz. The active antenna measurements were used to verify the total antenna performance through complete radio channel when the device was provided with the human proximity sensor system.

2.3 Sensor measurements

Sensor measurements used in Papers I-II, were performed with a laboratory-made test arrangement (Fig. 4) consisting of a phone chassis / PCB, antenna under test and a bottle of index liquid representing a phantom hand. The test arrangements provide stability and reproducibility for the measurements over several days. The hand measurement setup was calibrated with a hand-sized bottle and a quantity of IndexSAR liquid (2.15 dl) to be equal in size to a human hand in high- and low-load positions. A distance of 10 mm was selected as an average antenna to load distance normally used in the talk mode. Additionally at that distance the mechanical plate was reasonably easy to move without sticking contacts to the sample. A human hand effect on the antenna measured with different shapes and materials was also presented in [28].

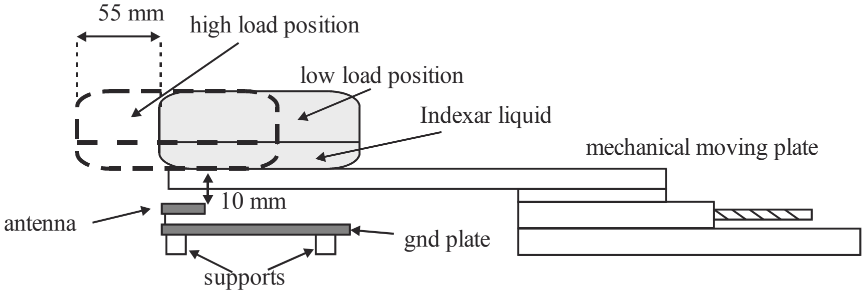

Fig. 4. Mechanical test arrangement (mainly plastic) for measuring sensor antenna performance, consisting of mechanical moving plate (motion distance of 55 mm) and bottle of Indexar liquid (2.15 l). The load is calibrated to be equivalent to that of the CTIA phantom hand. [Paper II, reproduced courtesy of The Electromagnetics Academy]

The finger measurement setup (Fig. 5) used in Papers III and IV consisted of the DUT and a movable load representing a phantom finger. The phantom finger is a finger sized plastic package filled with Indexar^{TM} liquid, providing the electrical parameters characterizing human tissue at high frequencies. It has a length of 60 mm and a diameter of 13 mm. The finger was connected to a large metal plate with a 50 cm long cable, joined with a metal ring (diameter 14 mm) which could be moved upright along the finger. The metal plate characterized the parasitic load of the human body, which electrical effect is based on the human body model (HBM) described in ANSI/ESDA/JEDEC JS-001 standard, 2010. The ring position was moved along the finger in the load calibration such that its electrical effect measured with the antenna matching was the same size as that of a real finger. The calibration was arranged at one fixed point in the middle of the antenna pattern. Further measurements were done with the low frequency sensor, which output is almost correlated with the Indexar^{TM} liquid and the metal object [42]. The corresponding measurement setup has not been previously presented in the literature. According to Paper IV it correlated well with human finger characteristics at 16 kHz frequency.

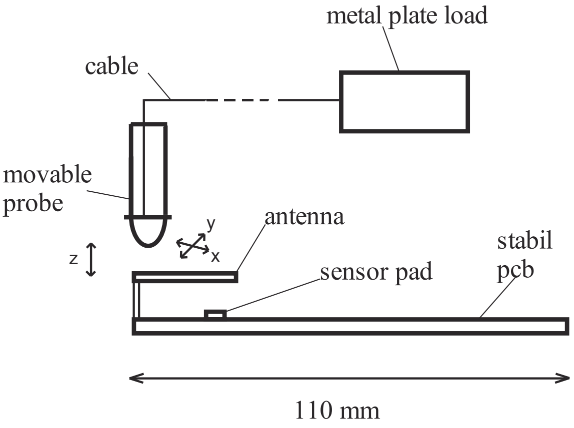

Fig. 5. Sensor sensitivity measurement bench. The DUT consisting of PCB, antenna and sensor, are in a fixed position. The movable probe (60 mm length, 13 mm diameter) filled with Indexar^{TM} liquid is connected with a metal ring (14 mm diameter) and 50 cm cable to the metal plate load (25 cm × 40 cm × 1.5 cm). Z was 3 mm, antenna to PCB distance 10 mm. [Paper IV, reproduced courtesy of The Electromagnetics Academy]

2.4 Antennas used in this thesis

Several antennas were equipped with capacitive sensors in the thesis. These antennas were not designed by the author, but by the research partners. The dual band (GSM900MHz/1800MHz) PIFA antenna was designed by Dr Markus Berg (University of Oulu, CWC), the dual band monopole (GSM900MHz/1800MHz) was designed by Dr Vamsi Palukuru (University of Oulu, Miklab), the single band CCE (900 MHz) was designed by Dr Jari Holopainen (Aalto University, SMARAD) and the single band CCE (1800 MHz) was designed by MSc Risto Valkonen (Aalto University, SMARAD).

The author discussed with particular people how to implement the capacitive sensors into the antennas. The 1800 MHz CCE antenna and the sensor were designed at the same time in collaboration with Risto Valkonen in order to optimize the space consumption and performance [26].

3 Performance of capacitive antenna proximity sensors

The objective of the chapter is to study the functional characteristics of whole hand proximity detection in the phone and also the technical characteristics of antenna integrated sensors.

The antenna integrated sensor represents the combination of a high frequency antenna and low frequency sensor, where the antenna pattern works as a sensing element. It provides a high sensing area but also potential signal interaction problems in the device. In contrast, discrete sensors have a minimum sensing area but signal interaction problems can be avoided. The sensitivity of the discrete sensors is measured over a very small sensing area and close to adjacent metal objects such as the antenna and metal EMC shields.

3.1 Antenna induced load effect evaluated with capacitive sensor

The accepted basis of this research is that the proximity of human tissue decreases the electrical performance of the antenna [1–13]. The research hypothesis is that the capacitive sensor output increases in terms of increased user load. In order to evaluate the hypothesis of user-induced effects in a used antenna, the following measurements were arranged: the capacitance (16 kHz), absorption (1 and 2 GHz) and impedance mismatch (1 and 2 GHz) of the antenna as a function of different hand held positions. A capacitive sensor was integrated on a PIFA antenna and the low frequency antenna capacitance was measured to quantify the amplitude of the effects caused by different grip positions over the antenna. (See also Chapter 4.2. and Fig. 14 for setup details) Grip positions and the corresponding electrical effects were studied by measuring the total efficiency in the 900/1800/1900 MHz GSM bands (Fig. 6). Measurement details are presented in Paper I. When increasing the hand grip coverage (total of 55 mm) over the phone, the capacitance increased from 3.83 pF to 4.45 pF at the highest load. The sensitivity of the antenna integrated sensor is then 11.3 pF/m. At the same time the peak total efficiency decreased from 53% to 16% in the 900 MHz band and from 47% to 21% in the 1800/1900 MHz band, respectively. Capacitive output increased in proportion to decreased total efficiencies in the measured bands.

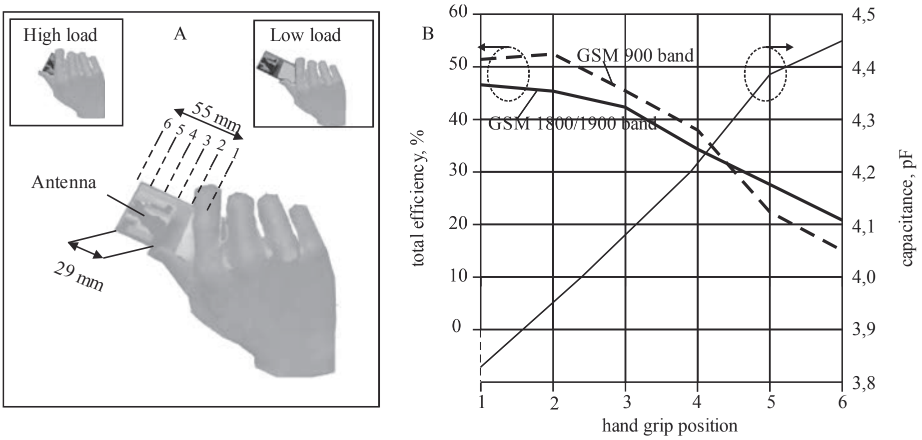

Fig. 6. (A) Hand grip positions from 1 to 6 (current position is 3), where the antenna was totally covered by the hand. The tip of the thumb sets the position. The increment step of grip positions is 11 mm, (B) Capacitance and total efficiency of the triple-band PIFA antenna with different hand grip positions. [Paper I and II, reproduced courtesy of The Institution of Engineering and Technology and courtesy of The Electromagnetics Academy]

The absorption and matching losses of the PIFA were calculated by measuring the total antenna efficiency and the antenna matching. The results are presented in Fig. 7. The absorption loss (900 MHz) starting from 1 dB at position number 1 increased up to 4.8 dB at position number 6. The matching loss starting from 0.6 dB increased up to 3.9 dB respectively. In the 1800 MHz band, the absorption loss started from 0.2 dB and increased nearly to 6.7 dB, whereas the matching loss remained around 1 dB in all measured positions. The absorption loss dominated the total loss of the antenna. The characteristics are clearly seen at the high band and similar loss behaviours are presented in [11, 12]. 900 MHz and 1800 MHz antenna bands have different matching loss characteristics since the antenna excites from the antenna pattern and two chassis wavemodes (1^{st} and 2^{nd} order) from the chassis of the device. The electromagnetic coupling factors between the fundamental resonance and chassis wavemodes are modeled with ideal transformers [43]. Due to multiresonance behavior of the 1800 MHz band, PIFA can maintain at least one of total of two resonances at the radiation band whereas at 900 MHz band the only resonance moves out of the band in loaded conditions.

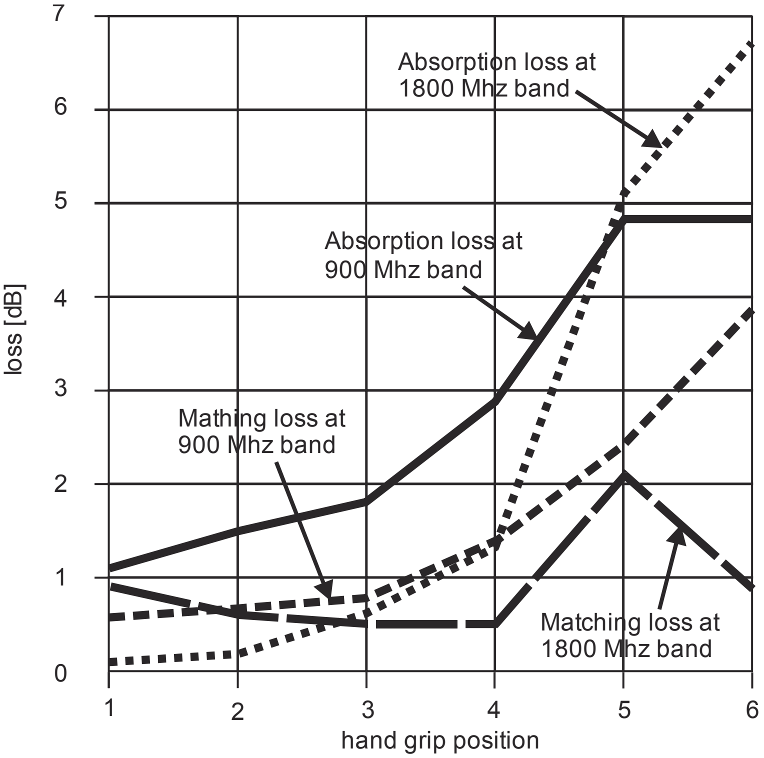

Fig. 7. Hand grip induced absorption and matching losses in PIFA antenna at 900 MHz and 1800 MHz frequencies. [Paper II, reproduced courtesy of The Electromagnetics Academy]

In conclusion, the total loss of the antenna cannot be estimated by measuring antenna matching, especially when two resonances are used in the same band (1800 MHz). However, the change in capacitance and total efficiency are well correlated. The absorption loss was difficult to evaluate with the matching sensor. In ultra wide band (UWB) antennas such as in [29], the absorption loss improves the reflection coefficient because the resistive component is increased and the imaginary part is less affected. So UWB antennas can utilize the capacitive sensing technique, whereas a traditional matching sensor is largely useless.

Furthermore, the capacitive sensors can measure every antenna in a multi antenna system, but RF matching sensor senses only the currently used antenna.

The characteristic opens new insights for MIMO (Multi Input Multi Output) antenna systems [30–33] and signal processing methods because the antenna array can be optimized in terms of the user load in handheld devices. Existing research papers have utilized the super-antenna definition, where the human user is considered as a part of the antenna characteristics. By using the capacitive sensor the user effect can be accurately separated from other antenna environmental effects. New user information that is not seen in existing MIMO studies is available after implementing the sensor system. According to studies [8, 34] the user effect can decrease the antenna performance for 40% of the time in the talking mode, which makes it worthwhile to apply compensation. The browsing mode was not measured.

3.2 Discrete sensors for user proximity detection

Discrete capacitive sensors can be utilized in applications where either whole hand detection or single finger detection is needed. Discrete sensors have to be physically smaller than the antenna of the phone in order to avoid extra losses being induced into the antenna. Discrete sensors were studied in Paper II as a whole hand sensor and in Papers III-IV as a single finger sensor. Corresponding small capacitive sensor research is presented in [21, 24] and larger sensors in [20, 22], respectively.

3.2.1 Two electrode discrete sensor for whole hand detection

The technical performance of discrete two electrode sensors is presented in order to evaluate whole hand detection capability. Sensors were used on both sides of the phone in order to increase the distance between electrodes and to maximize the detection range. Measurements results are presented in Paper II.

The mechanical test arrangement depicted in Chapter 2.3 was used for measurements of two electrode sensors. Commercial capacitance measurement circuit AD7747 (Analog Devices) was used in the thesis. It has high-resolution capacitance-to-digital converter and the architecture has high resolution (24-bit bit resolution), high linearity (±0.01%), and high accuracy (±10 fF factory calibrated). The AD7747 circuit`s input range is ±8 pF (differential) and up to 17 pF for common-mode (single-ended) capacitance. Two electrode discrete sensor utilized the AD7747 as differential mode. The circuit was placed on the backside of the PCB and lines were conducted through vias to the electrode areas.

The differential mode of the AD7747 measures additionally the capacitance between two C_{in} pins and the shield pin. The ground plane of the phone is relatively large compared with the sensor electrodes. Any parasitic capacitance

(C_p) between C_{in} pins and the ground plane is able to affect on the result. For a larger parasitic capacitance, the AD7747 uses a compensation method called shield function. The output of the shield pin is basically the same signal waveform as the output of the C_{in} pin. So the ground plane is driven to the same voltage potential as the C_{in} pin and no mutual ac current is existed. Parasitic capacitance does not affect on the C_{in} charge transfer and hand movements in close proximity of the ground plane can be effectively excluded from the results.

Some individual cases of sensor outlines and locations along the ground plane of the phone are presented in Fig. 8. PIFA prototypes were provided with two electrode sensors 2 × 3 mm located at varied positions on the PCB. Side positions of the ground plane as well as the sensor size were studied order to find the most sensitive placement and size for the electrodes. A parasitic load is higher and electrical field distribution is more divergent in large electrodes compared with smaller ones. Related parasitic-object load interactions are presented in [22].

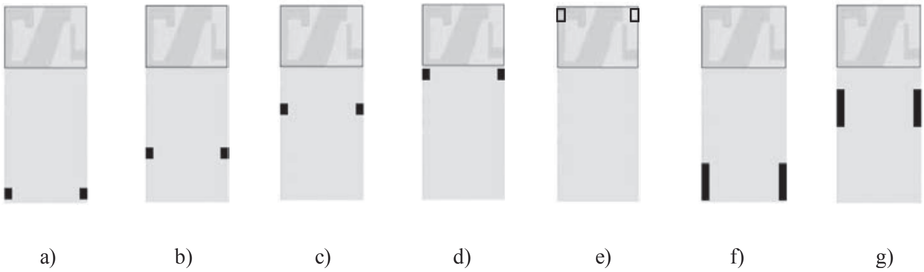

Fig. 8. Two electrode sensor used for whole hand recognition. From bottom end (a) to upper end (e) electrodes on PCB were tested with larger ones (f, g). The best performance was achieved with smaller electrodes at the bottom end (a). [Paper II, reproduced courtesy of The Electromagnetics Academy]

The initial capacitance value of the two electrode sensor was 300 fF (Fig. 9). Sensitivity was highest at the electrode location (a) at the bottom end of the phone (0.53 pF/m) and it decreased as the electrode location approached the antenna end. The worst electrode location was determined to be under the antenna element at the top end of the phone (e). Large electrodes at the bottom end and centre of the phone were slightly more insensitive (0.44 pF/m) than corresponding small electrodes in particular electrode locations. The electric field distribution in terms of the proximity object is different between large and small electrodes. With PCB thickness of 1.6 mm, current electrode areas (5 mm^2) and hand grips, brought out the structure that is more sensitive if equipped it with small electrodes. The electric field distribution is localized more in the air than inside the substrate.

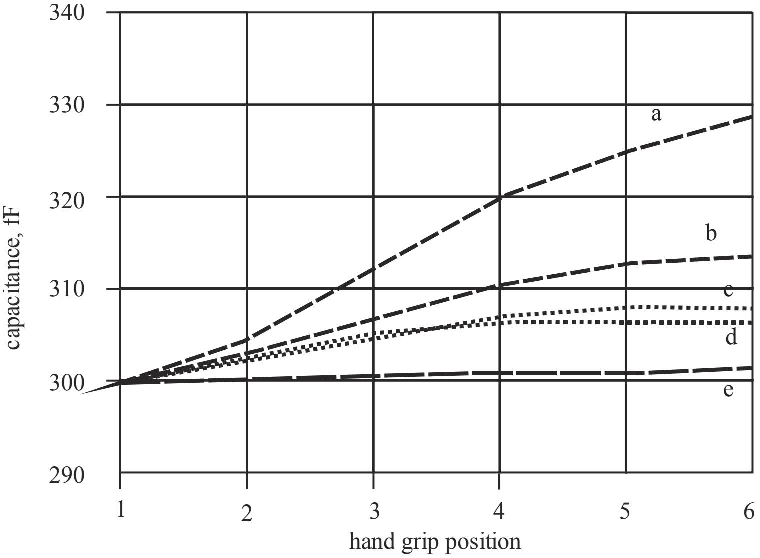

Fig. 9. Two electrode sensor sensitivities measured in terms of electrode positions along the phone. The most sensitive position was at the bottom end of the phone (0.53 pF/m) and the worst was behind the radiator (0.02 pF/m). [Paper II, reproduced courtesy of The Electromagnetics Academy]

3.2.2 One electrode discrete sensor for finger detection

The sensitivity of the single discrete sensor was measured by changing the relative physical locations of the antenna and sensor. Details of the research are presented in Paper IV (sensitivity) and in Paper III (antenna losses).

One electrode sensor was measured and optimized in terms of the capacitive coupling element (CCE) antennas at 900 and 1800 MHz and verified with a 1900 MHz PIFA. Fig. 10a presents a CCE antenna designed for 900 MHz GSM band and Fig. 10b presents a CCE antenna designed for 1800 MHz GSM band. In Fig. 10a the CCE antenna was located 5 mm above the corner of the ground plane and bent into an L-shape in order to maximize the coupling to the ground. The antenna was equipped with a metal line surrounding the inner corner of the CCE, representing the capacitive proximity sensor located 5 mm above the ground plane and 2 mm distance from the antenna. Fig 10a presents (as white colour) the long sensor providing 1 dB loss and (as black colour) the shortened sensor with 0.1 dB loss.

In Fig. 10b the 1800 MHz CCE antenna and the one electrode sensor are located on the PCB, at the same level and with 2 mm distance between sensor and antenna. The finger was able to be detected in close proximity to the antenna [26] and only 0.1 dB extra sensor induced loss was measured. The loss level was similar with a 1900 MHz PIFA presented in Fig. 10c.

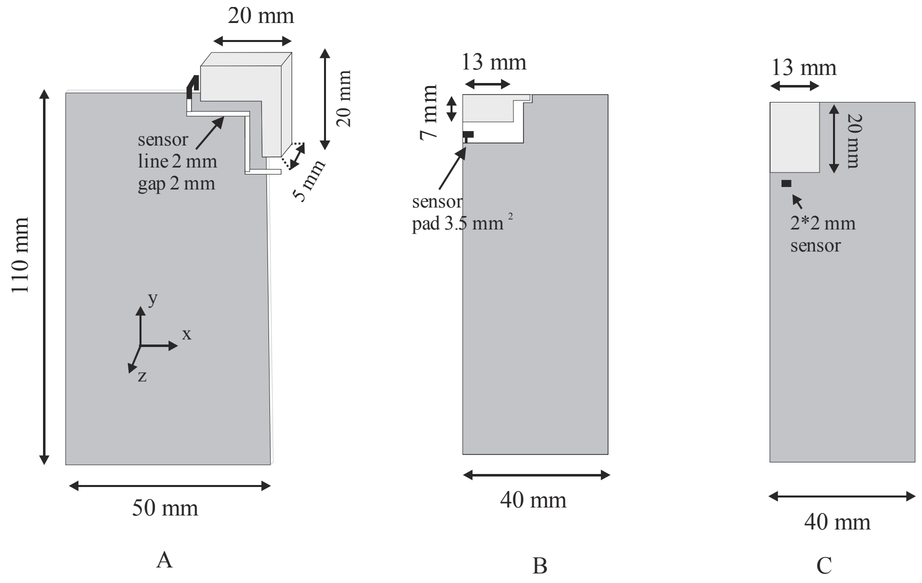

Fig. 10. (A) 900 MHz CCE, one electrode capacitive sensor with large (white) and small (black) electrodes, (B) 1800 MHz CCE, one electrode low loss capacitive sensor and (C) 1900 MHz PIFA antenna with low loss finger proximity sensor. [Paper III, © 2011 IEEE]

A direct calculation of a map of capacitive sensor sensitivity to permittivity variations, electrode displacements and electric field deformations has been described in [35]. Simulated electric potential maps used in the sensitivity analysis of different sensor topologies are presented in [21]. The sensitivity of the antenna proximity sensor located very close to or even behind the antenna element has to be carefully measured. Ideal sensing functionality requires that all possible directions, either on the front, top or sides of the phone, are able to be detected. In order to satisfy these requirements, at least two sensors have to be used in the application. The size of the sensor has to be small enough (< 4 mm2) to avoid a loss greater than 0.3 dB in the antenna. These requirements are satisfied by the antenna sensor structure and sensor sensitivity maps presented in Fig. 11. The sensitivity map results are presented with 2D and 3D pictures. In Fig. 11a two sensor locations were identified with insufficient sensor coverage in the lower corner of the antenna element. The sensor location results presented in Fig. 11b show sufficient coverage for the sensor. The capacitive range starts from 40.3 fF and reaches 43.3 fF at the highest load, providing the trigger level for the finger proximity to be, for example, 41.5 fF. The sensitivity over the movement range of 30 mm is 0.10 pF/m. However, the sensitivity is able to change in terms of sensor-load distance [43], which characteristic has to be taking into count in other applications. Figures 11c and 11d emphasize the sensor intensity information displayed as 3D pictures, revealing that the ground pin in close proximity decreased the sensor sensitivity. The antenna pattern can harm the usability of small sensors; if there is free space only under the antenna pattern, the sensitivity of sensors can hardly survive in real applications.

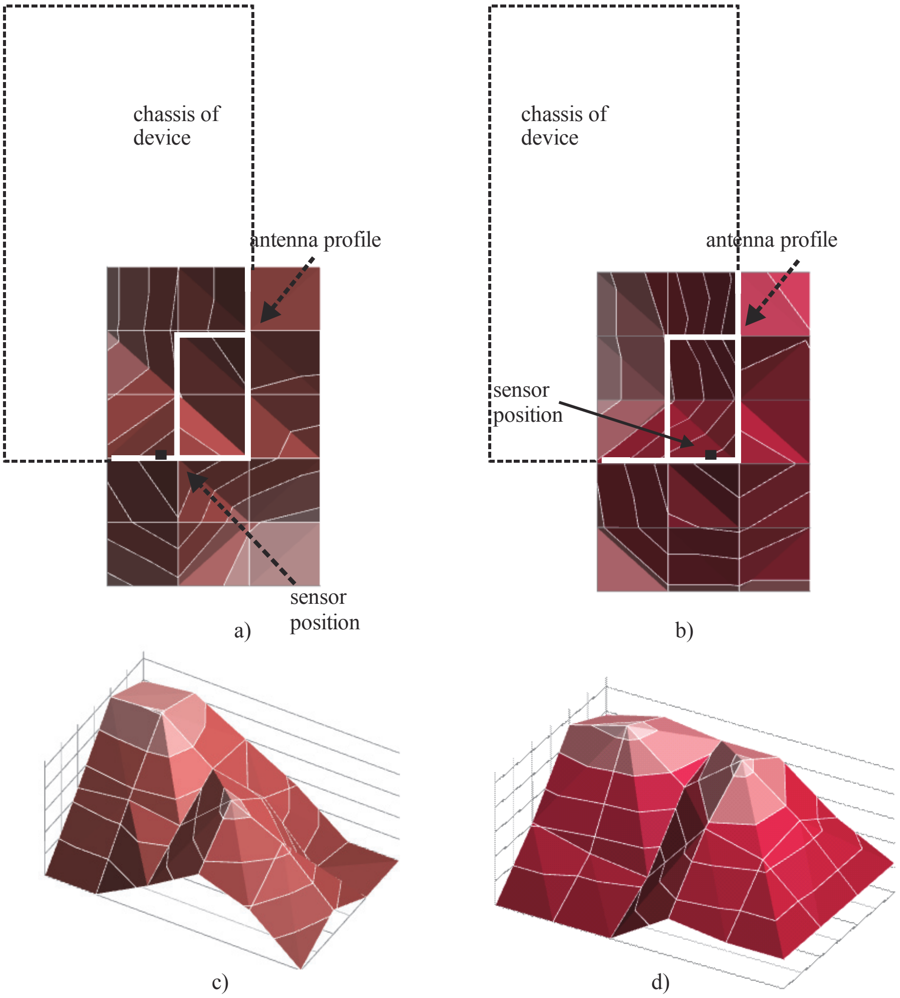

Fig. 11. Sensitivity output maps of one antenna and two discrete sensors. Antenna is with white outlines and sensors are with two peaks of colour map, (A) First sensor position left antenna corner uncovered, (B) Second sensor position presents sufficient cover, (C) First sensor position presented as 3D drawing and (D) Second sensor position presented as 3D drawing. [Paper IV, reproduced courtesy of The Electromagnetics Academy]

4 Antenna sensor interactions

In this chapter antenna sensor interactions are investigated. Sensor loss induced into an antenna should be avoided when using antennas either in the integrated or in the discrete sensors applications. Antenna sensor integration can harm the information signal due to the interfering interactions between two different signal sources connected to the same antenna.

4.1 Antenna sensor losses

Antennas have been integrated into smaller and smaller forms in recent years. A second technical trend has focused on the tunability of antennas [36, 37]. However, extra components always increase the antenna loss. In this thesis, antenna induced sensor losses are measured by measuring the total antenna efficiency with PIFA and CCE antennas in the 900/1900 MHz bands. The first measurements were aimed at selecting the sensor size with a 900 MHz CCE antenna and additional measurements were made in order to verify an acceptable loss level with other antennas, 1800/1900 MHz CCE and PIFA. Results were originally presented in Paper III.

At first, sensor induced total loss measurements were performed with the 900 MHz CCE antenna by varying the length of the sensor (Fig. 12a). The evaluation was made with full length (43 mm), half length (23 mm), quarter length (8 mm) and small length (1 mm) sensors and the results were compared to those of the reference antenna without the sensor. Antenna induced losses from 1.35 dB with full, 1.0 dB with half, 0.35 dB with quarter and 0.05 dB with small length were measured at 1 GHz, respectively (Fig. 12c). As a result it was found that only a few millimetres is a sufficient length for a capacitive sensor. In the following loss measurements 1800/1900 MHz CCE and PIFA (Fig. 12b) antennas were equipped with 4 mm^2 sensors. The loss results are presented in Fig. 13. The sensor forced PIFA to be re-matched to lower frequency than the original antenna due to increased parasitic reactance of the antenna. Thus original antenna has to be designed slightly higher frequency when equipped with the sensor. In the CCE antenna the sensor changed only its resistivity and the center frequency did not move.

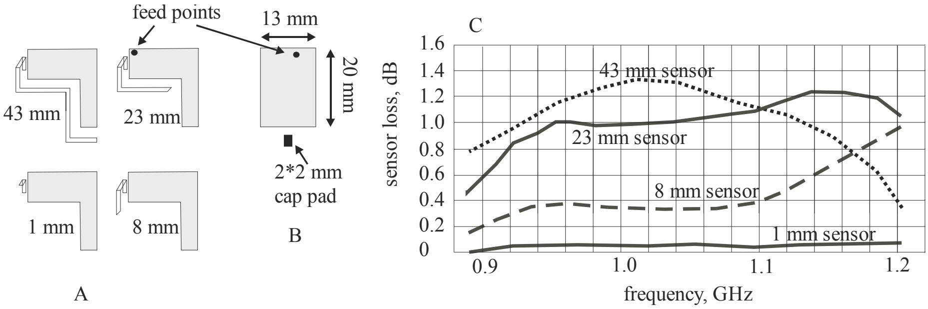

Fig. 12. (A) 900 MHz CCE antenna (top view) equipped with four different length sensors, (B) 1900 MHz PIFA antenna equipped with small sensor and (C) sensor induced losses at 900 MHz CCE antenna. [Paper III, © 2011 IEEE]

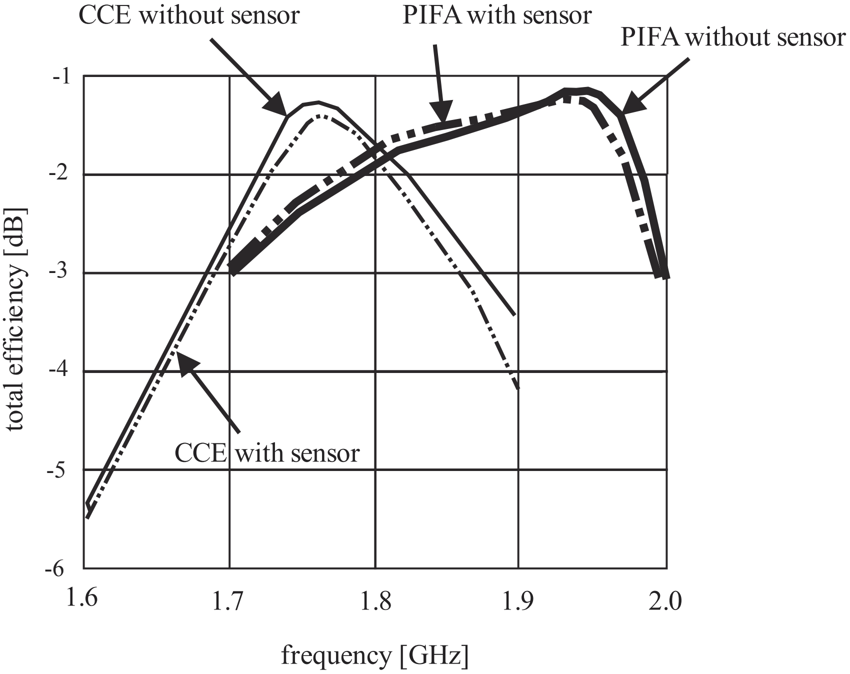

Fig. 13. Sensor loss comparison measured at 1800 MHz CCE and 1900 MHz PIFA antennas with and without capacitive sensor. [Paper III, © 2011 IEEE]

In CCE and PIFA antennas losses of 0.1–0.26 dB were measured at 1.6–2.0 GHz, characterizing an acceptable loss in both implementations. When roughly compared to commercial directional couplers (TDK, AVX, Panasonic) with a mean loss of 0.3 dB, only the small capacitive sensor is competitive. The total loss caused by the capacitive sensor and antenna tuning system would be 0.3–0.4 dB at 900 MHz band and 0.55 dB at 1800 MHz band. Antennas in mobile phones are more sensitive to low band than high band impedance mismatches [11, 12]. A constant 0.55 dB loss due to the de-tuning system compensating an occasional 1 dB hand induced mismatch loss would a questionable technical transaction at 1800 MHz band, whereas a constant 0.4 dB loss compensating an occasional 2–4 dB loss at 900 MHz band could be of beneficial technical merit.

4.2 Antenna interference

Antenna sensor ingeration increases the risk of radio frequency interference induced into the transceiver due to an unmatched antenna and spurious signals caused by the sensor measurement unit. Receiver interference issues are investigated in [38, 39]. In this thesis antenna sensor induced interference was measured with a real phone (Nokia 6021) by using active antenna measurements. Total radiated power, TRP, and total isotropic sensitivity, TIS, measurements were performed with two phones, a reference and a modified 6021. Typical TRP signal levels in the mobile phone around +20 dBm are not likely to suffer interference, but the TIS signal level of -100 dBm is susceptible to low level interference, explaining why resulting SNR (signal-to-noise) values are divergent. [Paper V]

Active measurements, presented in Fig 14a, were performed with a Nokia 6021 phone equipped with the capacitance measurement system in Fig 14b integrated to the 50 ohm impedance point between the TRX (Transceiver) and the antenna fed pin. An additional low pass LC-filter provided signal subtraction in the frequency plane.

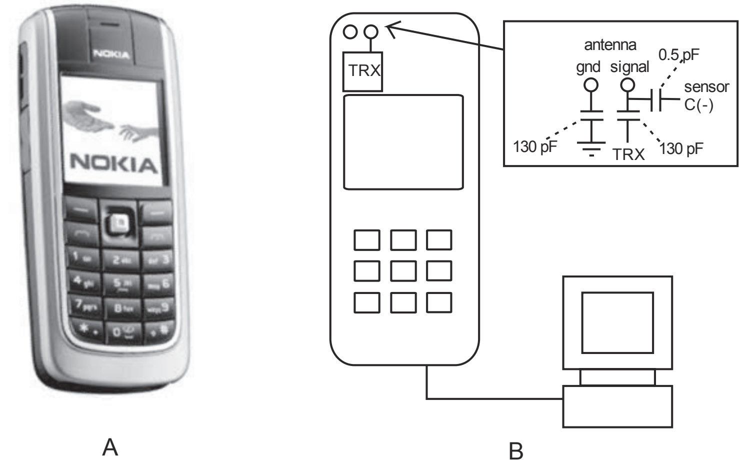

Fig. 14. (A) Nokia 6021 phone, (B) Antenna`s capacitance measured with sensor system consisting of capacitance circuit, measurement electronics and computer for collecting data. [Paper V, reproduced courtesy of The Electromagnetics Academy]

TRP and TIS measurements were realized using a Satimo Stargate antenna measurement chamber and additional total efficiency measurements were performed in the chamber with a cable phone 6021.

TRP and TIS measurements were measured with two Nokia 6021 phones. The first phone was kept without modifications working as a reference, and the second phone was equipped with the sensor implementation with a manual on/off switch. So the total number of analyzed cases is three. The measurements were repeated three times with different setups. In the first, measurement cycle capacitance values were collected with data cables. The second measurement cycle was performed with the battery operated sensing system. The third measurement cycle was performed also with the battery but the reference phone was changed in order to exclude product variations from the results.

4.2.1 TRP and TIS measurement results

The TRP results presented in Table I are organized by presenting three different measurement cycles, consisting of a reference phone (#1, #2) and capacitance on / off states. Six channels of GSM 900/1900 MHz bands were presented in the left column. The first measurement cycle was performed with data cables between the computer and the phone, and the second without the cables. Hence the effect of sensor signal cables could be distinguished. The third measurement session was a copy of the second except that the same 6021 was used both for the reference and the on/off modified phone, enabling the identification of phone manufacturing tolerances in the results.

As presented in Table 1, the modification caused 1.5–2.7 dB TRP deterioration at 900 MHz compared with the reference when data cables were used. After excluding cable effects the TRP deterioration was 1.1–1.5 dB and after excluding the product variation the TRP deterioration was 0.1–0.4 dB. The final results are close to the measurement system repeatability of 0.3 dB. Corresponding TRP deteriorations at 1900 MHz were under ± 0.5 dB. The on / off state margin was under ± 0.3 dB in all channels. In conclusion, the cable effect and product variation effect were clearly observed in the TRP results. According to these results, the sensor is applicable to real phone usage. All the results are distant from the limits set by network operators (23 dBm at GSM900 and 24.5 dBm GSM1900) [27].

Table 1. Total radiated power results [dBm] of Nokia 6021 phone measured from reference phone and modified phone with sensor on/off states. [Paper V, reproduced courtesy of The Electromagnetics Academy]

[MHz]	data cables used			no cables, #1			no cables, #2		
	ref	on	off	ref	on	off	ref	on	off
880,2	29,5	28	28,2	29,55	28,45	28,22	29,01	28,87	29
897,4	29,3	26,8	27,2	29,2	27,83	27,62	28,63	28,38	28,33
914,8	28,1	25,4	25,5	28,61	27,15	27	28,18	27,75	27,84
1850,2	27,4	27,9	28,0	26,98	27,45	27,21	26,69	26,88	26,62
1880	27,5	28,0	28,0	27,21	27,37	27,3	26,97	26,76	26,63
1909,8	27,6	27,5	27,4	27,2	26,88	26,63	26,42	26,12	25,98

The TIS results presented in Table 2 are organized in a similar way to the TRP results. The modification caused local interference in two channels: channel 914.8 MHz suffered up to 5.8 dB deterioration calculated between the on-state capacitive circuit and the reference. Additionally a signal drop of 3.5 dB was observed between on/off circuit states. A second interference was observed at 1880 MHz channel (3.2 dB). In conclusion, the TIS limit of -100 dBm at

GSM900 was not a problem but the -101 dBm limit at GSM1800/1900 was exceeded at 914.8 MHz.

Table 2. Total isotropic sensitivity results [dBm] of Nokia 6021 phone measured from reference phone and modified phone with sensor on/off states [Paper V, reproduced courtesy of The Electromagnetics Academy].

[MHz]	data cables used			no cables, #1			no cables, #2		
	ref	on	off	ref	on	off	ref	on	off
880,2	-103,6	-101,2	-101	-104,47	-102,5	-102,82	-103,7	-102,78	-102,86
897,4	-103,9	-101,9	-101,7	-104,77	-103,21	-103,38	-104,3	-103,09	-103,23
914,8	-103,2	-101,7	-101,3	-103,35	-99,6	-101,84	-102,7	-96,91	-100,43
1850,2	-104,6	-103,8	-104	-102,98	-103,29	-104,28	-102,5	-102,58	-102,68
1880	-104,5	-101,3	-103,1	-102,97	-103,44	-104,57	-102,9	-102,94	-103,07
1909,8	-104,1	-103,4	-103,5	-103,3	-103,45	-104,38	-103,2	-103,19	-103,31

The mean sensitivity of the receiver can be decreased when the antenna total efficiency is changed [40, 41]. The total efficiency can be decreased due to impedance mismatches, losses in the antenna itself or losses in the near environment such as a head phantom. TIS values were measured with cables, without cables and battery operated, which can change the antenna matching and efficiency and introduce extra loss into the system. However, the loss sources do not fully explain why there was interference in specific channels.

The device was studied and measured with a spectrum analyzer because the poor sensitivity on a single channel or channels could be caused by in-band noise or spurious signals coming from the capacitive measurement circuit. The operating measurement circuit caused high amplitude frequency multiplies on its output, these spikes were not sufficiently attenuated at high frequencies by the low pass circuit. A resonance peak with amplitude of -102.5 dBm was measured at 915.1 MHz, 300 kHz away from the TIS channel. The spike vanished after switching off the circuit. The characteristic predicts an uncertain usability for the antenna sensor integration in the current implementation but the problem could be solved with careful RF circuit design.

5 Conclusions

The main purpose of this thesis was to design and implement capacitive sensors into mobile phones in order to assess the user induced proximity effect in the antenna. The objective was divided into operational and technical objectives. Operational objectives were the detection of the whole hand and the detection of a single finger, whereas technical objectives included the antenna sensor implementation and the evaluation of capacitive sensor characteristics. The antenna sensor implementation was divided into antenna integrated and discrete sensor topics.

In this thesis a capacitive proximity sensor was used with a mobile phone antenna for the first time. Previously, corresponding operations have been performed with an antenna matching sensor. Capacitive sensors used as electrode elements were found to be applicable for whole hand recognition along the phone chassis and for finger recognition in close proximity to the antenna element. A pair of sensors located on the bottom end of the phone provided the best performance with the sensitivity of 0.53 pF/m and the worst location behind the antenna element decreased the sensitivity to 0.02 pF/m. In the case of single finger detection, the discrete capacitive sensor provided an antenna loss level of 0.05–0.20 dB at 1–2 GHz, which is equal or less than the currently used matching sensors. The sensitivity of single finger sensor was 0.10 pF/m. The physical range to detect a single finger in close proximity to the antenna element was sufficient when at least two sensors are used at different ends of the antenna element. The capacitive sensor could sense the user proximity effect regardless of antenna matching, which may be changed in a complex manner when more than one electrical resonance is used in the same frequency band or when matching is modified by a resistive component typically caused by human tissue absorption. In multiple-antenna applications, capacitive sensors could sense the loads of all antennas, whereas the matching sensor could only detect the antenna currently in use. This characteristic suggests the benefits of the capacitive sensor technique when considering new sensing measurement systems for the MIMO antenna environment in the future.

In the antenna sensor integration, the antenna element was utilized as a large sensing element, which is a method promising simultaneous use of a low frequency sensor and a high frequency antenna. As long as a high power RF signal (>25 dBm) is used, the sensor integration works. The sensor system caused 1.5–2.7 dB TRP deterioration at 900 MHz band when utilizing sensor data cables.

After excluding cable effects, the TRP deterioration was 1.1–1.5 dB and after excluding the product variation it was 0.1–0.4 dB being very close to the measurement system repeatability of 0.3 dB. TRP deteriorations at 1900 MHz band were under ± 0.5 dB. Thus the cable and product variation effects were clearly observed in the TRP results. With low power (< -100 dBm) signalling, the sensor system induced interferences in certain channels decreasing the sensitivity of the radio receiver. The circuit caused high amplitude frequency multiplies on its output and the result of resonance peak with amplitude of -102.5 dBm was measured at 915.1 MHz only 300 kHz away from particularly used radio channel. The jamming characteristic limits the usability of the integrated sensor. This is a drawback from the sensor`s sensitivity point of view since the antenna integrated sensor had the highest sensitivity of 11.3 pF/m compared with the pair of electrode sensors of 0.53 pF/m and the finger sensor of 0.10 pF/m.

Combining the results of integrated and discrete sensors, it can be concluded that the discrete sensor fulfills the technical and operational objectives set at the beginning of the thesis. Discrete sensors are applicable for antenna proximity sensor applications.

The concluding Table 3 provides a comparison of capacitive sensor utilizing systems and systems currently used in telecommunications. The main benefits of using capacitive sensors in particular systems are concluded. In one antenna detuning system, the capacitive sensor output is proportional to the dominating absorption loss, whereas the matching sensor predicts the matching loss. It is a characteristic that makes the overall performance of the capacitive sensor system higher. In addition, the capacitive sensor and matching sensor systems can be used simultaneously since they have unequal functional characteristics. The matching sensor is able compensate RF component and system variations and the received signal power can be measured. In the case of a two antenna spatial diversity system, the capacitive sensor provides new information, e.g. which antenna is covered by the user`s finger. The thesis did not evaluate the total achieved performance, but improved user information decreases the need for testing with the information signal. In systems with more than two antennas any additional information is potential to relieve complexes of current MIMO algorithms, which are currently based on the super-antenna approach. User proximity information provides benefits that increase energy efficiency and provide higher data speeds in handheld devices and finally a more attractive user experience. Further studies should be focused on exploiting the user proximity information in MIMO antenna systems.

Table 3. System comparisons for higher telecommunication performance.

Proposed capacitive sensing system	Currently used performance optimizing system
Capacitive sensor and detuning system (1 antenna)	Matching sensor and detuning system
Capacitive sensor and spatial diversity system (2 antennas)	Diversity algorithms (unused antenna load information is not available with current systems)
Capacitive sensor and MIMO antennas (>2 antennas)	MIMO algorithms based on super-antenna approach (unused antennas load information not available with current systems)

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