ANTENNAS FOR WIRELESS BODY AREA NETWORKS
ANTÉNY PRO BEZDRÁTOVÉ SÍTĚ PRACUJÍCÍ V BLÍZKOSTI LIDSKÉHO TĚLA

SHORT VERSION OF DOCTORAL THESIS
ZKRÁCENÁ VERZE DOKTORSKÉ PRÁCE

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1 Introduction

At present, the interest in communication devices is growing, since many modern applications and new technologies have been developed. These technologies such as remote sensing, telecommunication systems, biomedical engineering, healthcare, assisted living, etc. are finding way to our lives. We focus on applications which can make our lives easier and more comfortable.

The antenna is one of the most important parts of wireless communication systems. At present, the research of antennas and the wave propagation for body centric wireless communication has taken a prominent position due to the rise of the interconnection of different wireless sensors and devices around the human body. The new challenges were found in the fields of body area networks (BANs), body sensor networks (BSNs) and personal area networks (PANs).

Particularly, planar antennas take place in this type of communications due to small dimensions, thin profile, low weight and easy fabrication. The planar antenna for body communications can be wide band, narrow band, implantable, flexible etc.

Untypical parameters of planar antennas might be expected from the planar antennas since the human body is a unique area with varying mechanical, electrical and magnetical properties. Moreover, a complex scenario of the body centric wireless communication includes additional phenomenon like human mobility and operation in diverse environments.

The design of an efficient body centric wireless link has to begin by understanding the radiation and propagation of electromagnetic power in proximity of human bodies. For this reason, we performed rigorous electromagnetic simulations using various human body models. The elementary investigation could be done on simplified, single or multilayer human body models, where we strictly define material properties such as dimension, relative permittivity and conductivity. For advanced simulations, we have to consider more details in the model such as the skin, the muscle, the inner organs, the bones etc.

The thesis is aimed to determine antenna parameters affected by the proximity of the human body. The critical parameters comprise the antenna impedance matching, polarization properties and radiation patterns.

From the viewpoint of the frequency band we have many potential possibilities ranging from low frequencies to terahertz. The industrial, scientific and medical (ISM) radio bands are one of the opportunities.
2 State of the Art

In the literature we can find approaches which are focused on the design of antennas operating in proximity of human bodies. Generally, each approach is proposed for very specific applications and frequency bands. The applications can be divided into three fundamentals sections - the off-body communication, the on-body communication and the in-body communication.

The integral part of the investigation of the mention phenomena are human body models or numerical phantoms, which are used for theoretical analyses and computational simulations.

Higher frequency bands around 60 GHz seems to be a promising solution to body communications thanks to small dimensions of RF components and antennas, high free space losses (providing spatial separation of channels), high data rates and a wide available spectrum (57 to 64 GHz). The propagation of electromagnetic waves in this frequency interval can be characterized by several distinctive features, such as a high atmospheric attenuation due to the resonant oxygen induced absorption, and large reflection and absorption due to the strong dielectric contrast between the skin permittivity and free space [1].

2.1 Human body models

For the research of interactions between the human body and electromagnetic waves radiated from devices, we use tissue equivalent numerical models (numerical phantoms) or experimental phantoms instead of a real human body. The interactions comprise both an influence of the human body on the performance of devices and an influence of EM waves on the human body.

In principle, two types of numerical phantoms exist.

- A simplified phantom is created by lossy homogeneous dielectrics or multilayered dielectric structure. This simplified phantom can be used to evaluate EM dosimetry, e.g.

- A voxel phantom is a whole-body model. Such a phantom can comprise a very high spatial resolution model, classifying over 40 different types of tissues, based on the magnetic resonance imaging; X-ray computed tomography and high computer performance. [2].

The theoretical phantom is described in [3]. The used tissue types include skin, fat, muscle, cortical bone and bone marrow. The thickness of each tissue type is chosen in reference to the typical, anatomically representative human tissue thicknesses (see Chyba! Nenalezen zdroj odkazů.).

Authors of [4] describe the development, the accuracy and the limitations of four anatomical whole body models (34 year old male, 26 year old female, 11 year old female, 6 year old male) of creating the virtual family.
2.2 Body centric communication

Recent development in wearable computer technology has inspired the creation of a wide range of devices that can be carried by their user in a pocket or otherwise attached to their body. This new technology should be a successor to mobile phones, which have become smaller and more convenient for personalized operating over the last few decades [5]. Nowadays, a number of body-centric communication systems have been developed for specialized applications, such as fire fighters, astronauts, military and health care. Many applications areas even overlap, such as security, identification and finance.

There are concepts of an implantable wireless device that can act as identification, a wallet and a key [6]. Another concept investigates a sensing of human activity or physiological signals and the integration of sensors to an operation device. The physiological signal includes all major vital signs (temperature, blood pressure, pulse, heart activity etc.).

The concepts of a body area networks (BAN) or personal area networks (PAN) cover a range of communications needs and related requirements. These networks can be classified as:

a. Off-body: Since the channel is off the body in the surrounding space, only one antenna in the communications link is on the body. Influence of the human body on antenna properties can be suppressed by exploiting sufficiently large ground plane. At present, off-body systems operating 60 GHz are more and more popular.

b. On-body: Since most of the channel is on the surface of the body, both antennas will be placed on the body. In order to reach an acceptable attenuation of the channel, vertically polarized antennas are required.

c. In-body: Since a significant part of the channel is inside the body, implanted transceivers have to be used. Due to strong attenuation of human tissue, in-body links have to operate at low frequencies.
3 Dissertation Objectives

The previous part of the thesis has shown examples of existing concepts of antennas for body-area networks. Existing concepts of antennas motivate researchers to minimize dimensions, simplify the fabrication process, properly shape the radiation pattern and reach proper polarization properties.

The antenna concept, which does not use any conventional structure and meet all requirements related to the desire radiation pattern, impedance matching, polarization properties and small dimensions, has not been successfully designed and optimized yet (a multi-objective optimization might be advantageous).

Hence, I have defined the following objectives of the dissertation:

- Creating the simplified human body models.
  I will design simplified human body models in order to reduce the computational time needed for the analysis and optimization of body area network antennas. The simplified models will be optimized to provide similar results like complex numerical models and measurement in a specific range of frequencies and specific locations on the body.

- Formulating methodology of the synthesis of the antenna operating in proximity of human body.
  I will describe a general synthesis approach to the design of the antenna operating in proximity of human body models. This approach will include the problems of interaction between an antenna and a human body.

- Multi-objective optimization of an on-body communications link.
  The designed antennas will be used to create an on-body communication link. Parameters of this link will be optimized to meet the conflicting requirements. Therefore, multi-objective approaches will be applied.
4 Numerical and experimental models of tissues

I focused my research on the properties of antennas in proximity of the human body models and I studied their behavior. I compared a few types of antennas for body area networks and look for the best solutions from the view point of the radiation patterns, impedance matching, polarization properties and small dimensions.

Because of mentioned properties, it is required to study tissue models to understand phenomena related to the electromagnetism, composition of these models and the dependence of the model to accuracy of the simulations. According presented feature, following part describing the human body composition to understand the electromagnetic approach to body centric communications. This approach consists of the frequency dependent dielectric properties, power absorption by human tissue and specific absorption rate and penetration depth of the electromagnetic energy related to the operation frequency. All these phenomena make me possible to create the simplified human body models in order to reduce the computational time needed for the analysis and optimization of body area network antennas.

4.1 Human body composition

The elements of the human body can be viewed from different micro- or macroscopic levels such as the atom, the molecule, the cell, the tissue and internal organs. If an external electromagnetic field irradiates the human body than the cellular and tissue structures could be in danger.

At the level on the cellular structure, electrical properties of the human body are defined by the properties of the cell membrane and the conductive intercellular fluid and extracellular fluid [8].

- Cell membrane.
- Extracellular fluid.
- Intracellular fluid.

At the tissue level, electrical properties of the human body can be also characterized by the different moisture content and composition. The tissue is approximately differentiable according to the method of uniting, because the cells unite in the extracellular fluid composing the tissue. The tissue can be divided into:

- Low water content tissue.
- High water content tissue.

It is possible to say, that the fat is special type of tissue, because the moisture content varies. The fat in the abdomen is similar to muscle, by contrast the other part of the body it may be similar to bone.
4.2 Frequency dependent dielectric properties

Because of the measurement setup need to be in contact with living tissue, it is not possible to make measurement on living tissue to determine their parameters. A problem associated with the mentioned problem is obtaining samples. For this reason, the most studies used a dead tissue. Except human tissues, researchers used freshly killed sheep, which was measured within 2 hours of death. Measurement was made in frequency range from 10 Hz to 20 GHz. As the frequency varies significantly, evaluation of the dielectric constant is based on summation of 4-Cole-Cole expressions, 

\[ \varepsilon(\omega) = \varepsilon_\infty + \sum_{n=1}^{4} \frac{\Delta \varepsilon_m}{1 + (j \omega \tau_m)^{2 \alpha_m}} + \frac{\sigma_j}{j \omega \varepsilon_0} \]  

where \( \varepsilon_\infty \) is the material permittivity at terahertz frequency, \( \varepsilon_0 \) is the free space permittivity, \( \sigma_j \) indicate the ionic conductivity and \( \varepsilon_m, \alpha_m, \tau_m \) are material parameters for each dispersion region.

The specific frequency significantly changes the penetration depth. At lower frequencies around 100 MHz the penetration depth is significant and it is used for in-body communications. The penetration depth is reduced with increasing the frequency [9].

4.3 SAR

The specific absorption rate (SAR) quantifies the power absorbed per unit mass in an object exposed to an RF field and can be considered the fundamental parameter in field of health risks of electromagnetic power absorption in the body. Many national regulatory agencies (e.g. Federal Communications Commission (FCC), require the peak spatial-average SAR associated with a certain wireless handset to be evaluated to ensure the compliance with their rules (Code of Federal Regulations and guidelines of the FCC). The maximum of SAR value is based on standards such as IEEE or the International Commission on Non ionizing Radiation Protection.

Evaluating the SAR distributions associated with such devices is a complex task, usually accomplished by measurement techniques or numerical modeling. One method of measurement specific SAR is the measurement of electric field strength in tissue equivalent medium.

The SAR in the phantom can be determined by measuring the increasing temperature, equation (4)[9], or by electric field measurement, equation (5) [8].

\[ SAR = \frac{c_1 \Delta T}{\Delta t} \bigg|_{t=0} \]  

\[ SAR = \frac{c |E|^2}{\rho} \]  

Here, \( c_1 \) is the specific heat capacity, \( \Delta T \) is the change in temperature, \( \Delta t \) indicates the exposure time, \( \sigma \) identifies the electric conductivity, \( |E| \) specifies the magnitude of the electric field intensity vector and \( \rho \) is the mass density of the medium [11], [12].
4.4 Penetration depth

The human body is a lossy medium, and the wavelength is shortened due to the real part of dielectric constant. Both the magnitude and the phase of the dielectric constant depend on frequency. Therefore, the attenuation inside the human body is also frequency dependent. The wave number $k$ is complex [8],

$$k = k' - jk'' = \omega \sqrt{\mu_0 \varepsilon_0} = \omega \sqrt{\mu_0 \varepsilon_0} \left( \varepsilon_r - j \frac{\sigma}{\omega \varepsilon_0} \right) \tag{4}$$

where $\mu_0$ is the permeability of free space, $\varepsilon_0$ denote the permittivity of the free space, $\varepsilon_r$ is specify the relative permittivity, $\sigma$ identify conductivity and $\omega$ is angular frequency.

Now, we have to consider a semi-infinite large plane made from a homogeneous human tissue with the plane wave of normal incidence. The electric field intensity in human tissue can be describe as a function of the propagation distance $d$ along the $x$ axis by equation [8]

$$E_z = E_{z0} e^{j(\omega t - kd)} = E_z e^{-kd} e^{j(\omega t - kd)} \tag{5}$$

where $E_{z0}$ is the electric field at the air/body boundary, $e^{-kd}$ denotes the attenuation term in the direction of propagation with [8]

$$k'' = -\omega \sqrt{\mu_0 \varepsilon_0} \text{Im} \left[ 1 - j \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r} \right] \tag{6}$$

The wavelength in human tissue is

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r \Re} \left[ 1 - j \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r} \right]} \tag{7}$$

Mentioned wavelength $\lambda$ shortening effect yields a propagation speed $v$ slower than light in the human body

$$v = \frac{\lambda}{t} \tag{8}$$

From (7) determined that the electric field attenuates exponentially with $k''$ inside the human body. In the distance where the field $E_z$ is attenuated to $\frac{1}{e^{0.368}}$ or -8.68 dB

$$\delta = \frac{1}{k''} \tag{9}$$

of initial value $E_{z0}$ is called the skin depth or penetration depth [8]
5 Experimental vs. numerical phantoms

Numerical analysis of a wireless body area channel requires phantoms based on realistic data, which can be obtained by a complicated process based on sectioning a tissue. Inhomogeneous phantoms consist of several internal organs, which are indispensable for analysis of medical implants, in-body communication, and for evaluating the distribution of SAR inside the body.

If studying an on-body channel at microwave frequencies, the penetration depth is very small. In this case, internal organs play an irrelevant role, which allows us to simplify phantoms. In this case, phantom can be homogeneous or eventually stratified. Stratified phantoms contain several layers which model skin, fat, muscles etc.).

5.1 Physical body phantoms

Phantoms can be divided into several groups according to the frequency range, the type of tissues to be represented, and the final state of the phantom after the manufacturing process i.e. the liquid one, the solid (dry) one and the semi-solid (gel) one.

- A liquid phantom, involves a container for holding the liquid inside. The liquid exhibits the same electrical characteristics as the tissues in the human body, at a specific frequency. The electrical characteristics of the liquid can be change by modifying of recipes, which commonly contain sugar or diacetin or diethylene glycol butyl to control permittivity and salt to set up conductivity. This type of a phantom can be used in SAR studies, since the direct measurement of the electric field inside the phantom with a small probe is possible. The container is usually made of a fiberglass material. The relative permittivity of the container should be smaller than 5, the loss tangent smaller than 0.05, the thickness should be around 2 mm for the frequency range from 0.8 GHz to 3.0 GHz. The shape of the container can vary depending on specific requirements (modeling a head, a whole body etc.). This type of the phantom provides an opportunity to study field distributions inside tissues, but it does not allow us to study field distribution close to surface. Moreover, the liquid presents the homogeneous medium, which is not representing an internal structure of the human body. The phantom has an important advantage in terms of the easy of production [5].

- A solid phantom, can provide good option for modeling internal structures of the body. In addition, the whole phantom can be inhomogeneous and keep required shape for a period of time.

The thermography is probably only way how measure SAR. The SAR can be evaluated from the temperature rise caused by electromagnetic wave. The possible measurement of the electromagnetic wave propagation around, as well as inside, the body is a unique advantage of solid phantoms.
The solid phantom can provide prominent mechanical and dielectric characteristics, which are stable for a long time due to the absence of water. On the other hand, the fabrication of such phantoms is much more complicated compared to liquid phantoms since the recipes can combine a ceramic, a graphite powder, a silicone rubber, a carbon fiber or a conductive plastic. These substances need to be manufactured using special and expensive equipment, high-precision procedures, high temperature and pressure [5].

- A semi-solid phantom is based on a water substance molding in the desired design. This procedure enables us to remove a container use by liquid phantoms. As water substance materials like a jelly can be used. The recipes consist of TX-151 [10] or agar as the gelling medium [12], while polyethylene powder and sodium chloride are used to control the permittivity or the conductivity of the final material. Due to evaporating, the water semi-solid phantom is stable for a short time only.

5.2 Human body phantoms

It is possible to find more than 80 different tissue types, which are reconstructed as three dimensional unstructured triangulated surface objects. The pixel size of the model of a newborn child is approximately 0.5 mm x 0.5 mm x 1.0 mm to more than 5 mm for some adult models. Naturally, small anatomical details are irrecoverably lost if a harsh resolution is chosen for the models. The important parameters such as thickness of the skin and fat layers can be represented as an integer multiple of the voxel dimension. These layers are important for the radio frequency absorption at the surface of the body [4].

Anyway, we have designed simplified human body models to reduce computing time with respect to the complexity of the models. The simplified models contain rougher mesh than the complex models. From the viewpoint of propagation of electromagnetic waves, all described layers are lossy dielectrics of a specific thicknesses and complex permittivity.

Other important phenomenon is heating of the tissue. Heating is complicated to be simulated because the heat dissipated from the tissue mainly by the flow of the blood. The heat is caused by electromagnetic field emitted by the antenna.

The tissue model is a block with the base of the several wavelengths. The height of the block is given by the thicknesses of the layers representing the skin, the fat and the muscle. The length of the arm model is several wavelengths. The radius of the arm is given by the thicknesses of layers representing the skin, the fat, the muscle, the bone cortical and the bone marrow. The length of both models could be adapted for various wavelengths.
6 Antennas operating in proximity of human body models

6.1 Triangular slot antenna

In this Section, a non-conventional triangular slot monopole is studied to be used in a wireless link operating in proximity of a human body. Thanks to the planar structure, the antenna exhibits low weight, low profile and compact size. The coplanar waveguide (CPW) is used to feed the slot monopole.

The double triangular slot antenna consists of two equilateral triangles (see Fig. 1). The first triangle is directly connected to the feeding line. The second triangle is connected to top of the tuning stub. Both triangles are spliced together by the top side. At the beginning, the initial dimensions of the triangular slots were set to the half wavelength and the quarter wavelength, respectively. When the antenna was moved to the proximity of a human body model, dimensions had to be tuned to achieve a sufficient impedance matching in the frequency band of operation. The final dimensions are given in TABLE I. The CPW feeder is designed following the procedure described in [7]. The width of the signal strip is \( a = 1.5 \) mm and the gap between the signal strip and the coplanar ground plane is \( b = 0.58 \) mm [14].

![Fig. 1. CPW-fed double triangular slot antenna.](image)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>a1</th>
<th>a2</th>
<th>l1</th>
<th>l2</th>
<th>l3</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values [mm]</td>
<td>16.71</td>
<td>8.94</td>
<td>3.10</td>
<td>4.19</td>
<td>8.50</td>
<td>19.00</td>
<td>16.45</td>
</tr>
</tbody>
</table>
Fig. 2. Frequency response of the reflection coefficient at the input of the CPW-fed double triangular slot antenna for different distances from the planar tissue model.

Fig. 3. Simulated frequency responses of the reflection coefficient at the input of the CPW-fed double triangular slot antenna distance $d = 5$ mm from the planar tissue model (black solid line) and from complex voxel (Duke) model (red dashed line). Frequency response simulated in free space (blue dotted line) and measured above the planar phantom (green line).

The simulated frequency response of the reflection coefficient at the input of the slot monopole antenna is shown in Fig. 2. The figure shows the parametric analysis of the distance between the slot antenna and the tissue model. In the distance $d = 0$ mm, we can observe that the value of the reflection coefficient completely differ from other dependencies. This phenomenon is caused by a direct contact between the antenna substrate and the tissue model. In this situation the tissue model creates a ground plane of the antenna which completely changes properties of the slot antenna and its feeding structure.
Now we can turn our attention to the distance $d = 5\text{mm}$. For this distance, the slot antenna meets requirements for the frequency band of operation. In this distance the slot antenna interacts with the human tissue and moves to the required resonance with center frequency 5.8 GHz.

Increasing the distance between the antenna and the tissue above 5 mm ($d > 5\text{ mm}$), properties of the slot antenna converge to free space parameters.

Simulated and measured frequency responses of the reflection coefficient at the input of the designed antenna are depicted in Fig. 3. Since we measure the slot antenna of the slot antenna in a wrong distance from the phantom ($d \neq 5\text{ mm}$), the resonant frequency was shifted to 5.25 GHz.

The antenna shows good impedance matching: the reflection coefficient of the antenna is below $-20\text{ dB}$ in the whole operating frequency band.

Radiation patterns simulated at 5.8 GHz both in the E plane and in the H plane are shown in Fig. 4. The results demonstrate a good agreement of simulations using different human body models and measurements. For the comparison, we considered radiation patterns of the antenna simulated in free space also. The gain computed at 5.8 GHz was $G_1 = 3.1\text{ dBi}$ in free space and $G_2 = 8.86\text{ dBi}$ in proximity of the layered model. For the Duke model of the human body, the gain $G_3$ is similar compared to the gain of the antenna in proximity of the layered model. Moreover, the gap between the slot antenna and tissue must be strictly kept. Then antenna properties are excellent from view point of radiation patterns and impedance properties. These circumstances indicate correctness of both the model in simulations and the manufactured phantom.

Finally, designed antenna can be concluded to be a good candidate for off-body communication. Unfortunately, a radiation into the tissue is a disadvantage. On the other hand the gain in the requested direction (out of body) is sufficient.

![Normalized radiation patterns](image-url)
6.2 Koch slot loop antenna

In this section, the Koch snowflake (one of the oldest fractal structure) is used to create a slot loop antenna. In order to keep physical dimensions of the antenna constant when prolonging the magnetic current length of the loop, the fractal Koch geometry can be applied for shaping the loop. We follow the procedure of the iterative synthesis of the Koch fractal described in [15]. This procedure does not increase the dimension of the antenna, but the physical length of the wire is prolonged by a factor \((4/3)^n\), where \(n\) is the number of the iteration.

The designed slot loop antenna is of a shape of a Koch snowflake created from the third iteration of the Koch fractal. The width of the slot is 0.40 mm. The length of each element is given by \(l_e = l_s \times (4/3)^n\), where \(l_s\) indicates the length of a straight wire and \(n\) is the number of the iteration. The length of the element is chosen to be half wavelength in free space.

In the top point, the slot of the Koch snowflake is interrupted by a narrow strip of the width \(w_2 = 0.50\) mm. This interruption plays a role of a serial susceptance in the circuit of a magnetic current to be used for tuning the input impedance of the antenna in resonance (see Fig. 5).

The loop antenna is fed by a CPW with the characteristic impedance of 50 \(\Omega\). The width of the signal strip is \(A = 1.50\) mm and the gap between the signal strip and the coplanar ground plane is \(B = 0.20\) mm. We follow the procedure of the design of CPW feeder in [15]. The CPW feeder has a tuning stub of the length \(L_s = 3.04\) mm and the width \(W_s = 1.26\) mm. A proper impedance matching of the slot antenna can be achieved by setting the length and the width of the tuning stub [15]. The total size of the antenna \(X \times Y\) is 25.30 mm \(\times\) 16.00 mm (see Fig. 5).

![Koch slot loop antenna](image)

Fig. 5. Koch slot loop antenna
The antenna was designed for the substrate Arlon 25N with the dielectric constant \( \varepsilon_r = 3.38 \), the loss tangent \( \tan \delta = 0.0025 \), and the height \( h = 0.762 \text{ mm} \). The prototype of the antenna was completed by an end launch connector.

The Koch slot antenna was manufactured and the prototype was placed to the distance \( d = 5.00 \text{ mm} \) from the agar phantom. In this configuration, we measured the frequency response of the reflection coefficient at the antenna input, and radiation patterns in the \( xz \) plane and the \( yz \) plane.

The frequency response of the reflection coefficient of the simulated and measured antenna is depicted in Fig. 6. In the frequency range from 5.725 GHz to 5.875 GHz, the impedance matching is lower than \(-15 \text{ dB}\). At the resonant frequency 5.8 GHz, the reflection coefficient at the antenna input is lower than \(-20 \text{ dB}\). The results show a good agreement of measurements and simulations using different human body models.

In order to demonstrate the antenna sensitivity to proximity of the human body the parametric analysis was done (see Fig. 7). In these simulations, the simplified human body was used because of good agreement of the frequency response of the reflection at the antenna input between phantoms and measurement to save the computation time. If the distance between the slot aerial and human body model is \( d = 0 \text{ mm} \) the human body model creates the ground plane of the slot aerial and the aerial is mismatched. At the distance \( d = 5 \text{ mm} \) the antenna becomes matched at the resonant frequency \( f = 5.8 \text{ GHz} \), the minimum value of the frequency response of the reflection coefficient at the aerial input is \( S_{11} = -41 \text{ dB} \). Increase of the distance \( d \) leads to the inferior interaction caused by the proximity of the phantom and the resonant frequency moves to a lower frequency \( f = 5.5875 \text{ GHz} \) in free space.

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Fig. 6. Frequency response of the reflection coefficient at the Koch slot antenna input.
The comparison of measured radiation patterns (the agar phantom) and simulated ones (the simple layered phantom) of the antenna are shown in Fig. 8. Radiation patterns are normalized. The differences in radiation patterns are affected by lossy dielectric objects (phantoms), which absorb and reflect the radiated electromagnetic waves. The interactions depend on the relative permittivity and thickness of all materials, and on the distance between the antenna and the phantom.

The antenna was shown to exhibit the directional radiation with the maximum in the direction perpendicular to the plane of the substrate. Sensitivity of the antenna to the proximity of a human body is relatively low. The antenna exhibits a satisfactorily wide impedance bandwidth. Impedance matching can be tuned by a stub in the CPW feeder. The input impedance is positively influenced by a susceptance inserted into the loop of the magnetic current.

For simulations, we used two human body models (a layered one and a voxel one). For measurement, we used a phantom made from a modified agar gelatin. Measured and simulated results exhibited a satisfactory agreement.

Hence, the Koch slot loop antenna can be a good candidate for WBAN applications.
6.3 Slot antenna array on circular SIW resonator for on body communication

In this section, a planar antenna for on-body communication is described. In order to meet requirements of on-body communication, a slot antenna array on a circular substrate integrated waveguide (SIW) resonator was developed. The resonator is fed by a SIW. Thanks to SIW, a parasitic radiation of feeding is minimized [17].

The structure consists of two dielectric layers:

- The bottom layer forms a feeding line. The feeding line is created by SIW operating in the fundamental mode TE10. The end of the SIW is shorted. The beginning of the SIW is connected to a SIW-to-microstrip transition. The transition is printed on the top side of the layer and is matched to 50 Ω (see Fig. 9, TABLE II).

- The upper layer supports four antenna radiators (circular slots). The bottom side of the upper layer is covered by a continuous metallic layer. The top side of the upper layer contains a circular patch completed by four circular slots (see Fig. 9, TABLE II).

The edge of the circular patch is completed by pins creating a circular SIW resonator. The diameter and the distance of vias of the resonator influence the resonant frequency of the resonator and modes to be excited in the resonator. Moreover, the vias make the resonator less sensitive to the surrounding environment.

The via in the center of the structure is directly connected to the ground plane in the feeding line. The via in the center gives us a null in the radiation pattern in the direction perpendicular to the antenna plane and supports an almost omnidirectional radiation in the horizontal plane.

Four slightly shifted (0.5 mm) vias in the center of each slot change the distribution of the equivalent magnetic current in the slot and decrease the resonant length of the slot.

Obviously, the designed antenna meets requirements on low profile, low weight and compact size. The antenna was designed for on-body communications in the ISM frequency band 5.8 GHz (ITU-R 5.138, 5.150 and 5.280).

The antenna is optimized for the maximum impedance bandwidth (the reflection coefficient lower than −10 dB). For the fabrication, the microwave substrate ARLON 25N (the relative permittivity ε_r1 = 3.38) was selected for the upper antenna layer, and the microwave substrate FR4 (the relative permittivity ε_r2 = 4.3) was chosen for the bottom feeding layer.
For the simulation and the optimization of the antenna located close to a body, we used a simplified three-layer tissue model and a complex voxel Duke model.

**TABLE II. Numerical values of design of the antenna**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$L$</th>
<th>$W$</th>
<th>$r_1$</th>
<th>$r_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value [mm]</td>
<td>62.00</td>
<td>50.00</td>
<td>12.33</td>
<td>21.66</td>
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<td>Parameter</td>
<td>$r_3$</td>
<td>$d_{ia}$</td>
<td>$r_{in}$</td>
<td>$r_{out}$</td>
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<tr>
<td>Value [mm]</td>
<td>22.90</td>
<td>0.90</td>
<td>5.88</td>
<td>6.65</td>
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<tr>
<td>Parameter</td>
<td>$L_{SIW}$</td>
<td>$W_{SIW}$</td>
<td>$w_1$</td>
<td>$l_1$</td>
</tr>
<tr>
<td>Value [mm]</td>
<td>65.50</td>
<td>50.00</td>
<td>20.69</td>
<td>2.69</td>
</tr>
<tr>
<td>Parameter</td>
<td>$d_{SIW}$</td>
<td>$w_2$</td>
<td>$l_2$</td>
<td>$w_3$</td>
</tr>
<tr>
<td>Value [mm]</td>
<td>2.90</td>
<td>5.40</td>
<td>8.00</td>
<td>1.65</td>
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<tr>
<td>Parameter</td>
<td>$l_3$</td>
<td>$l_4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value [mm]</td>
<td>5.00</td>
<td>52.50</td>
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Frequency response of the reflection coefficient at the input of the designed antenna is depicted in Fig. 11. A slight difference between the simulated responses is caused by a different meshing of numerical models.

Now, let us turn our attention to radiation patterns. Radiation patterns in the horizontal plane (in parallel to the surface of the body) are shown in Fig. 10. The antenna exhibits almost omnidirectional radiation.

Radiation patterns in the vertical planes for the antenna in free space are depicted in Fig. 10.
The described array consisting of four slots etched on the top side of the SIW resonator can be understood as an array of equivalent electrical monopoles placed into the center of slots. Thanks to this, architecture, a planar structure of the antenna was achieved.

The developed ring slot antenna array was optimized for the operation in the ISM band. The antenna was requested to operate in proximity of the human tissue. Outputs of simulations and measurement showed that:

- Requirements on the impedance matching were met in frequency range from 5.6 GHz to 6.2 GHz.
- The bandwidth is relatively wide (about 10%). This is the positive influence of the stable excitation field formed by the SIW resonator.
- The radiation pattern is omnidirectional in the plane of human skin.
• The maximum of the radiation is elevated. In order to minimize the elevation and force the antenna to radiate on the plane of skin maximally, distribution of magnetic currents in slots has to be optimized.

• Parameters of the developed antenna are not influenced by the proximity of human body significantly. This conclusion is valid both for the simplified layered phantom and the complex voxel one.

6.4 Millimeter wave slot array for on-body communication

The slot array described in the previous chapter can be redesigned for the operation in 60 GHz ISM band. The structure consists of two dielectric substrates:

• The upper substrate (see Fig. 12) forms an antenna radiator constructed from the circular patch completed by four circular slots. Around the circular patch, pins are located to create a circular SIW resonator. The SIW resonator forms a proper field distribution for the excitation of slot elements. Moreover, the SIW resonator makes the antenna array less sensitive to the proximity of human body. The resonant frequency of the SIW resonator is influenced by the diameter and the distance of pins mentioned above. In order to create an almost omnidirectional radiation pattern of the array in the horizontal plane, a tuning via in the center of the patch is used. The tuning via is directly connected to the ground plane and gives us a null potential in the structure.

• The bottom substrate (see Fig. 12) is designed as a feeding structure. The feeding structure exploits the substrate integrated wave guide (SIW) operating in the fundamental mode TE10. The end of SIW is shorted because of the excitation of the upper resonator. The beginning of the SIW is directly connected to the waveguide operating at 60 GHz [17], [18].

![Fig. 12. Array of four circular slot antennas on the top of SIW (left), SIW feeding network (right), dimensions are in mm.](image-url)
The omnidirectional slot array was designed as a transmit antenna. As a receive antenna, we used a directional SIW horn at different positions of a human body to characterize WBAN links experimentally. Outputs of simulations were verified by measurements.

For computer simulations of the slot antenna array, we used a simplified model of human tissue consisting of three layers simulating a skin, a fat and a muscle. The tissue model was of the dimensions larger than $15 \lambda \times 30 \lambda$, where $\lambda$ is wavelength in free space at the frequency 60 GHz.

The antenna array was analyzed in proximity of a voxel Duke model. The analysis validated the results of simulations using the simplified tissue model [19].

The antenna array was placed to the proximity of a layered tissue model, and the wireless link was studied from the viewpoint of frequency responses of the magnitude of transmission coefficient and reflection coefficient. Numerical experiments comprised several configurations:

- The slot array in the transmission mode was rotated to verify omnidirectional radiation in the horizontal plane.
- The distance between the surface of the tissue model and the planar horn antenna in the receiving mode was varied to characterize the influence of a human body on parameters of the SIW horn.

Frequency response of reflection coefficient at the input of the designed transmit antenna is depicted in Fig. 13. A slight difference between responses is caused by a different meshing of numerical models. In order to perform analyses in a reasonable time, coarse meshes were used.

![Simulated frequency response of reflection coefficient](image)

Fig. 13. Simulated frequency response of reflection coefficient at the input of the designed transmit antenna in free space (blue solid line), on layered tissue model (red dashed line), on voxel tissue model (green solid line).

Simulated radiations patterns in 3D are depicted in 0 and Fig. 14. The patterns can be considered as omnidirectional ones.
Fig. 14. Three-dimensional radiation pattern of the designed transmit antenna in free space (left), on layered tissue model (right).

In order to characterize transmission of a signal along the human body at the frequency 60 GHz, we have computed magnitude of the transmission between the transmit antenna (the slot array) and the receive antenna (the SIW horn). The distance between antennas was 100 mm, which corresponds to the distance from a breast to a waist in the voxel model (see Fig. 17).

Fig. 15. Simulated transmission between the designed transmit slot antenna and the SIW horn receive antenna for different gaps between the receive horn antenna and the layered tissue model.
Fig. 16. Simulated transmission between the designed transmit slot antenna and the SIW horn receive antenna for different rotation of slot antenna in proximity of the layered tissue model.

Fig. 17. Duke model with the SIW horn receive antenna (top) and the designed transmit slot antenna (bottom).

Fig. 15 shows the frequency response of the transmission between the designed transmit antenna and the SIW horn receive antenna. The SIW horn was placed to different distances from the the layered tissue model, the transmit antenna was fixed. The frequency response of the transmission between the designed transmit antenna and the SIW horn antenna in proximity of human body is shown in Fig. 16.

The measurement was done to validate simulated results. First, we will turn our attention to reflection coefficient at the input of designed antenna. The measured results in Fig. 18 shows that the minimum of reflection coefficient was shifted less than 0.5 % (0.5GHz) to the higher frequency and reached lower value $S_{11}^{\text{measured}} = -33.1$ dB in proximity of the phantom. The deviation from simulated results could be caused by manufacturing tolerances and simulation errors.
Second, the radiation was measured and the results are shown in Fig. 19 and Fig. 20. The measurement was done only for the front half-plane of designed transmit antenna because of measurement setup does not enable to measured it in this configuration. The rear half plane of designed transmit antenna is shielded by feeding structure. The simulation and measured results are in good agreement. Moreover, the curves disclose of variances caused by manufacturing tolerances and simulation errors.
Finally, transmission between the designed transmit slot antenna and the SIW horn receive antenna was measured. The transmission coefficient was measured at the laboratory workplace (see Chyba! Nenalezen zdroj odkazů.) at single frequency $f_{\text{trans}} = 60$ GHz.

Measurement experiments comprised several configurations (see, TABLE III, Chyba! Nenalezen zdroj odkazů., TABLE IV and TABLE V):

- The distance between the surface of the tissue model and the planar horn antenna in the receiving mode was varied to characterize the influence of a human body on parameters of the SIW horn.

- The slot array in the transmission mode was rotated to verify omnidirectional radiation in the horizontal plane.

- The distance between both antennas was changed to characterized the influence of this distance to transmission coefficient.

### TABLE III. Measured transmission between the designed transmit slot antenna placed in various distance from phantom and the stabilized SIW horn receive antenna in distance 10.00 mm from phantom at frequency 60 GHz, distance between antennas is 100 mm.

<table>
<thead>
<tr>
<th>Distance from phantom [mm]</th>
<th>Transmission [dB]</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>-51.91</td>
</tr>
<tr>
<td>5.00</td>
<td>-44.88</td>
</tr>
<tr>
<td>10.00</td>
<td>-45.51</td>
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<td>15.00</td>
<td>-47.52</td>
</tr>
<tr>
<td>20.00</td>
<td>-49.93</td>
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### TABLE IV. Measured transmission between the rotated designed transmit slot antenna placed 5 mm from phantom and SIW horn receive antenna placed 10 mm from phantom at frequency 60 GHz, distance between antennas is 100 mm.

<table>
<thead>
<tr>
<th>Rotation [°]</th>
<th>Transmission [dB]</th>
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<tbody>
<tr>
<td>0</td>
<td>-45.20</td>
</tr>
<tr>
<td>15</td>
<td>-43.10</td>
</tr>
<tr>
<td>30</td>
<td>-45.80</td>
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<tr>
<td>45</td>
<td>-49.80</td>
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<td>60</td>
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<td>75</td>
<td>-44.22</td>
</tr>
<tr>
<td>90</td>
<td>-50.80</td>
</tr>
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</table>

### TABLE V. Measured transmission between the rotated designed transmit slot antenna placed 5 mm from phantom and SIW horn receive antenna placed 10 mm from phantom at frequency 60 GHz, distance between antennas is various.

<table>
<thead>
<tr>
<th>Distance between antennas [mm]</th>
<th>Proximity of phantom</th>
<th>Free space</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00</td>
<td>-44.88</td>
<td>-47.18</td>
</tr>
<tr>
<td>150.00</td>
<td>-51.10</td>
<td>-48.86</td>
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We can conclude that we have studied an array of circular slot elements for an on-body communication at 60 GHz in this chapter. Circular slots enabled us to create a planar antenna which is equivalent to perpendicular monopoles. Thanks to the SIW feeder, we can excite a proper mode of magnetic currents in slots.

The geometry of the antenna array was optimized to obtain the desired impedance matching lower than -10 dB ($S_{11} < -10$ dB at frequency 60 GHz) and the desired shape of the radiation pattern in the horizontal plane (omnidirectional radiation).

The designed slot antenna array is able to cover surface of the human body by a surface electromagnetic wave.

As a receive antenna, we have used a SIW horn at the different positions on the surface of a human body. That way, we were able to characterize WBAN links experimentally. Simulations were performed in CST Microwave Studio using a simplified human tissue model and a complex voxel Duke model.

After all, in this section the slot antenna for frequency band 60 GHz was designed and manufactured (see Fig. 21), the frequency response of reflection coefficient at the input of antenna was simulated and measured. The on-body communication link was created and studied from the view point of the transmission coefficient at 60 GHz.
7 Conclusions

The dissertation thesis is focused on the antennas, which can operate in proximity of human body to implement wireless body area networks, body sensor networks and personal area networks.

First part gives an overview of the present research in the area of body centric communications and shows the challenges in this field. The off-, on- and in-body communications are described too.

The human body models, which have been already created for the simulation of body-centric antennas are shown here and compared. The simplified human body models reduce time in the simulations process. These models will be extensively compared with commercial, complex, voxel human body models to demonstrate the agreement. The research is performed from the perspective of placing antennas in proximity.

Two antennas, namely triangular slot antenna and Koch slot loop antenna, have been designed, simulated and measured from the viewpoint of impedance matching and radiation patterns. When antennas are placed close to human body models we can observe the shift of resonance frequency. The electromagnetic field is dominantly radiated in the direction from models to free space, which can be use for the off-body communication link.

For on-body communication link was designed one type of antenna, namely slot antenna array on circular SIW resonator. The antenna array was modified into two antennas operating at different ISM frequency band (5.8 GHz and 60 GHz). These antennas were studied in proximity of human body from the view point of frequency response of reflection coefficient at the antenna input, radiation characteristic and transmission coefficient. The electromagnetic field is dominantly radiated in plane of antenna array, which is complementary to the dipole antenna but with suitable dimensions. The communication link was created in range from 20 * λ to 30 x * λ (λ is wavelength in free space at specific frequency), which correspond to the distance from the breast to the waist, and the several antenna configurations was simulated and measured.
8 References


# CURRICULUM VITAE

**Name:** Ing. Vladimír Hebelka  
**Born:** The 5th of August 1986 in Boskovice, Czech Republic

## Education

<table>
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<tr>
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<td>2011 - 2015</td>
<td>Brno University of Technology, Department of Radio Electronics</td>
<td>PhD degrees, Electronic and Communications</td>
<td>Thesis: Antenna for Operation in Inhomogeneous Environment</td>
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<td>2014</td>
<td>European School of Antennas: Leaky Waves and Periodic Structures for Antenna Applications</td>
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<td>2012</td>
<td>European School of Antennas: Metasurfaces for Antennas: Canonical Surfaces, EBG surfaces, Soft and Hard Surfaces, Gap Waveguide Technology</td>
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<tr>
<td>2009 - 2011</td>
<td>Brno University of Technology, Department of Radio Electronics</td>
<td>Masters’s degrees, Electronic and Communications</td>
<td>Thesis: Panel Antennas for 5.6 GHz</td>
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<tr>
<td>2006 - 2009</td>
<td>Brno University of Technology, Department of Radio Electronics</td>
<td>Bachelor’s degree, Electronic and Communications</td>
<td>Thesis: Wideband Antenna for frequency range from 5 GHz to 10 GHz</td>
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## Languages

English, German, Spanish.

## Specialization:

Research, analysis and design of antennas, modeling and simulation of microwave and RF structures, antenna measurement.
Abstract

The dissertation thesis is focused on the proposing a general synthesis approach to the design of the antenna operating in proximity of human body models. The critical parameters comprise the antenna impedance matching, polarization properties and radiation patterns. The elementary investigation is done on simplified human body models, where we strictly define material properties. For advanced simulations, we have to consider more details in the model. Simulations are confronted with the measurement on real samples. In this thesis we will include the problems of interaction between an antenna and a human body.