On-body Cavity-Backed Low-UWB Antenna for Capsule Localization

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Abstract

The paper presents a novel antenna operating at the lower UWB band (3.75–4.25 GHz), defined originally in IEEE 802.15.6 standard for Body Area Networks (BAN) applications. The proposed antenna is designed for biomedical application, wireless capsule endoscopy localization. In other words, the concerned application is dedicated to track a capsule, by means of an external device, swallowed by the patient to provide captured images of the Small Intestine (SI), essential part of the GastroIntestinal (GI) tract, and transfer them in real-time to the external device. In this context, antenna with and without cavity-backed structures, are presented and compared with the requirements for a receiving antenna in terms of directivity and bandwidth coverage in question. It was revealed that the cavity approach improved the antenna gain up to 8 dBi, at the 4 GHz center frequency, compared to 6 dBi without the cavity presence. Simulations were carried out using CST Microwave Studio, and the results were validated by measurements in proximity to human body. The antenna safety issue was assessed with CST SAR (Specific Absorption Rate) calculation, in compliance with IEEE/IEC 62704-1 standard. Results showed a maximum SAR of 0.112 W/kg and 0.005 W/kg at 4 mm and 30 mm antenna-skin distance, in the range of the SAR limit guidelines defined by safety standards. The cavity-backed antenna ability to penetrate the human tissues, to reach the small intestine layer was studied by means of CST voxel model and compared to a multi-layer model emulating the dielectric properties of the human tissues at 4 GHz. This analysis was conducted using power flow results and completed by the power field probes at the several tissue interfaces.

Keywords BAN · IEEE 802.15.6 standard · High gain · Small-intestine · WBAN · Capsule

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1 Introduction

Wearable antennas are in the interest of several novel applications [1–3]. Their involvement is significant, in particular in medical applications [4]. In this context, Wireless Body Area Networks (WBAN) comes to provide consistent guidelines to meet the scientific requirements [5]. One of them appealing to these antennas is wireless capsule endoscopy (WCE) localization [6, 7], since it requires an efficient designed on-body antenna to track the capsule movement inside the GastroIntestinal (GI) tract, in particular Small-Intestine (SI), of a patient [8]. The main focus is to have a directional antenna by maintaining its features, in terms of the covered bandwidth in close proximity to a human body (abdomen area) and to have the ability to reach the small intestine tissue. Last decades, many works have been oriented towards this kind of research topic by using different frequency ranges [9, 10]. However, the low Ultra Wide-band (UWB) band (3.75–4.25 GHz) is defined originally in IEEE 802.15.6 standard [11–13] and it is preferred to minimize the path loss caused by lossy human body tissues. Additionally, to improve the image resolution quality, the requirement is to assess the captured images from inside the small intestine. Thus, transfer them wirelessly in real-time to external devices is a crucial question, as discussed in [6]. Besides, in literature, several channel models were defined and investigated with the focus on the specific frequency range studied in this paper.

The aim of the paper is to further discuss a lately published antenna, operating at low UWB band, according to IEEE 802.15.6 standard. The structure is intended to wireless capsule endoscopy localization purposes. The paper defines the antenna designed according to two structures, single and cavity-backed antennas, presented in Sect. 2. On-body investigations using both antennas structures are provided in Sect. 3. Last section presents different perspectives of the present work. Simulations were carried out by using CST Microwave Studio, and validated in free-space and on-body study cases by measurements. The detailed investigations confirm a good suitability of the proposed cavity-backed antenna structure for the WCE localization.

2 Antenna Structure and Configuration Analysis

2.1 Simulation Results

This section presents an extended configuration analysis of a recently published UWB antenna [14], by distinguishing two approaches: Planar and cavity-backed antenna structures. The published work demonstrates that both antennas are directive and working at the low UWB band defined in IEEE 802.15.6 standard for WBAN applications.

As discussed in details in [14], a planar antenna was built at first stage, to which a cavity was introduced to back the planar antenna structure. The parametric configuration of the single antenna and its emplacement inside the cavity is detailed in Figs. 1 and 2 and the detailed parameter values are summarized in Table 1.

The main idea of including the cavity was to deviate the antenna radiation from Y-axis to Z-axis and further increase the antenna directivity to fit realistic scenario where the antennas are installed on the human body. For this aim, a metallic box of 0.5 mm-thickness acting as reflector was backing the planar antenna structure. The antenna was placed in the center of the cavity and its dimensions were discussed in [14]. The cavity overall size is 90.8 mm
(length), 86 mm (width) and 39.5 mm (height). In [14], both antenna structures were fed by directly connecting a waveguide port to the microstrip line. The planar antenna was embedded in the center of the cavity, as presented originally in [14]. This designed antenna had a simulated bandwidth of 3.61–4.46 GHz, and resonated at 3.85 GHz with −50.72 dB return loss, as presented in Fig. 3 by “Bodynets Antenna” plot. However, for this initial built model, the antenna input impedance was 71.82 + j9.46 Ω, as shown in Fig. 4, which is unsuitable to practical case. Later, by positioning the antenna on the cavity surface, with a distance about the cavity height of 30 mm, the upper frequency was increased to 4.76 GHz, as presented and known under the name “Prototype Antenna (Wo Cable)”, in Fig. 3. For this case, the antenna resonant frequency was shifted upwards to 3.96 GHz with a return loss of −39.12 dB and the antenna input impedance was slightly modified to 63.35 + j0.83 Ω. However, by applying a coaxial cable to feed the antenna, named “Prototype Antenna Wi cable” in Figs. 3, 4, 5 and 6, the −10 dB impedance bandwidth and the resonant frequency remain quite the

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| Ws        | 30.3       | W6        | 4          |
| Ls        | 25         | W7        | 9.5        |
| hs        | 1.6        | L1        | 20.14      |
| W1        | 3          | L2        | 2.9        |
| W2        | 16.4       | L3        | 12         |
| W3        | 3          | L4        | 2          |
| W4        | 13.15      | L5        | 7.14       |
| W5        | 13.15      | Cav       | 30         |

Fig. 2 The UWB cavity-backed built model and fed by coaxial cable in CST

Fig. 3 Simulated reflection coefficient of the UWB cavity-backed antenna

Fig. 4 Simulated input impedance of UWB cavity-backed antenna

Fig. 5 Simulated efficiency of UWB cavity-backed antenna

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same about 3.66–4.70 GHz and 3.97 GHz, respectively. The only difference is that the maximum return loss is decreased to −23.84 dB as shown in Fig. 3. It was concluded that, the input impedance is close to realistic case where the antenna is measured appealing to 50 Ω coaxial cable in order to connect the antenna to the measurement equipment, as presented in Fig. 4.

The cavity-backed antenna was predicted to radiate well over the frequency band under interest, as shown in Fig. 5. Additionally, from Fig. 6 is it clearly seen that the antenna maximum gain is stable over the studied frequency range, within the range of 8–9 dBi and 7–8 dBi for the case the antenna is placed inside the cavity “Bodynets Antenna” and at the cavity surface “Prototype Antenna (Wo Cable)”, respectively. It seems that the distance of the antenna from the cavity bottom has an impact on the reached gain.

One can conclude, as the distance separating the antenna ground plane to the cavity bottom increases, the gain decreases. However, the cable feeding does not have any effect which is good seen from practical point of view. The cavity-backed antenna has a good directivity slightly towards Z-axis with main values of 7.88 dBi, 7.63 dBi and 7.75 dBi at 3.75 GHz, 4 GHz and 4.25 GHz, respectively, as illustrated in Fig. 7.

### 2.2 Measurement Results

The cavity-backed antenna structure was prototyped and measured, as demonstrated in Fig. 8a, b. The reflection coefficient of the cavity-backed antenna was compared in Fig. 9 for the three previously listed antenna cases. Reported results show that the maximum measured reflection coefficient in free-space is −17 dB at 4 GHz with a covered −10 dB impedance bandwidth matching of 3.75–4.26 GHz.

The antenna was also measured for on-body scenario with a male person, wearing thin t-shirt, by placing the antenna randomly on the belly and the comparison result was
provided in Fig. 9. The resulting bandwidth was widened 3.32–4.86 GHz, while the resonant frequency was quite the same. According to Fig. 10, the cavity-backed antenna performs to radiate well and has a good measured gain of 7 dBi at 4 GHz. Back to related works, few researches were addressed to localize the capsule endoscope antenna in low-UWB band. In [15–18] the receiving antennas used in investigations are standard ones commonly used in diverse on- and off-body communications. Their limitations remain basically in low gain compared with the proposed cavity-backed antenna.

The measured radiation pattern of the cavity-backed antenna was compared to the simulated one as depicted in Fig. 11. Table 2 groups the comparison of the reported measured and simulated gain at 3.75 GHz, 4.00 GHz and 4.25 GHz, according to Phi = 0°, Phi = 90° and Theta = 90° cuts. The simulated and measured results are in good agreement, showing the maximum gain at Phi = 90° of 7.70 dBi, 8.00 dBi and 5.05 dBi against 7.17 dBi, 7.00 dBi and 7.12 dBi at 3.75 GHz, 4.00 GHz and 4.25 GHz, respectively. The slight difference in radiation pattern shape is justified by the current overflow over the coaxial cable due to the fact that the antenna is a balanced structure and the coaxial cable is unbalanced.

3 On-body Study

A detailed on-body study is presented in this section. Simulated and measured results are compared and discussed.

Fig. 10 Measured maximum gain and efficiency of the UWB cavity-backed antenna

Fig. 11 Simulated and measured radiation pattern comparison in dB of UWB cavity-backed antenna at a 3.75 GHz, b 4.00 GHz and c 4.25 GHz

3.1 Simulation Results

To simulate the on-body use of the proposed cavity-backed antenna, a multi-layer model was used to emulate the human body (Small Intestine area). The multi-layer model is based on 6 layers, which are skin, fat1, muscle, fat2, SI wall, SI content, with the features [19–22] are described in Table 3. By assuming the visceral fat (Fat2 layer) the most influencing component in the abdomen area for different persons, two different thicknesses were considered of 25 mm and 73 mm for “Thin” and “Fat” person case. The thickness of the remaining layers was fixed to 1.4 mm, 25 mm, 12 mm, 1 mm and 20 mm for Skin, Fat1, Muscle, SI Wall and SI Content, respectively. The size totaling the multi-layer is 220 mm length, 220 mm width, and 87 mm height. This sub-section investigates the cavity-backed antenna performances in close proximity to human body. The antenna separation distance $d$ is defined as the distance between the cavity edge and the skin surface as illustrated in Fig. 12a, which is easy to reproduce accurately in measurements. The 30 mm distance roughly corresponds to half near field region of the studied antenna. Next, Laura voxel model was used to approach the realistic measurement application. As depicted in Fig. 12b, c, the antenna performances were assessed on the “Navel” and “Back” sides with the closest separation distance from the skin layer, roughly estimated 2 mm and 4 mm, respectively, because of the body shape. The boundary conditions were fixed in such way to enclose the model
cut, as shown in Fig. 12b, so as to avoid any power overflow. Figure 12c provides an insight of the inner body tissues according to X-cut section. It is important to evaluate the antenna interaction with different parts of the body because the antenna will serve as a monitoring device held on the patient and handled by the medical doctor. Besides, with the extension and the meandered-shape of the SI tract, it is necessary to analyze the antenna behavior with different body parts.

In the following investigations, the cavity-backed antenna model corresponding to the antenna prototype is considered. The antenna has a $-10$ dB bandwidth of $3.92-4.62$ GHz and $3.59-4.45$ GHz, in both thin and fat study cases, for $d=4$ mm and $d=30$ mm, respectively, as shown in Fig. 13a. It can be concluded that the human tissue thicknesses do not affect the antenna performance in terms of matching, whereas the separation distance $d$ does. By comparing the on-body measured case in Fig. 9 with the simulated ones for $d=4$ mm presented in Fig. 13a, little divergence is remarked because it is challenging to manually design a realistic model. Moreover, the reflection coefficient of the antenna using voxel model is plotted in Fig. 13b for navel and back cases as known under “Navel_Voxel” and “Back_Voxel” names, respectively. Results show that the upper frequency is constant of $4.45$ GHz while the lower frequency knew a slight increase from $3.68$ to $3.74$ GHz for “Back_Voxel” case. Interestingly, this time the on-body measured reflection coefficient matches closer the “Navel_Voxel” result.

The power pattern flows of the cavity-backed model for thin and fat persons with $4$ mm and $30$ mm separation distance using multilayer and voxel models can be found in [23, 24]. It is clearly visualized how the SI layer is reached even for fat person study case. For thin person, the power pattern not only reach the SI wall but it exceeds it to cover the SI content as well. These investigation results promote the cavity-backed antenna use for wireless capsule endoscopy localization.

3D directivity results for the aforementioned study cases using multilayer and voxel models are illustrated in Fig. 14. Maximum directivity (Max D) values are reported in Table 4. The antenna gain is averaging $-5$ dB at $4$ mm and $30$ mm distance from the multi-layer model. When using voxel model, a relatively raised gain of $0$ dB and $2.51$ dB was noticed on “Navel” and “Back” cases, respectively. This results strongly depends on the reported total efficiency values which enhance with the antenna-skin distance increase as presented in Table 4. Furthermore, the antenna matching in terms of input impedance of the UWB cavity-backed antenna is assessed as well. The investigation results are grouped in the same table showing that the antenna has a capacitive behavior for $d=4$ mm, while an inductive behavior is revealed for $d=30$ mm. According to the same table, it is noticed that when placing the antenna so close to the voxel model, the antenna has an inductive behavior. On the Navel, the resistance is about $45$ $\Omega$ compared to $29.3$ $\Omega$ on the back, which is caused by the different nature, in terms of the dielectric properties, of the surrounding realistic human tissues. Besides that, the antenna resistance remains quite constant averaging $54$ $\Omega$ for $d=4$ mm, while this parameter is increased about $60$ $\Omega$ for $d=30$ mm.

A detailed simulated and measurement study providing the free-space propagation, using the proposed cavity-backed antenna, was presented in [25]. Moreover, the channel propagation using the proposed cavity-backed antenna

### Table 2: Simulated and measured gains of UWB cavity-backed antenna per cut plans

| F [GHz] | Phi = 0° | Phi = 90° | Theta = 90° |
|---------|----------|-----------|-------------|
| 3.75    | 2.95     | 7.17      | -0.538      |
| 4       | 3.69     | 6.99      | 2           |
| 4.25    | 3.16     | 7.12      | 1.4         |

| F [GHz] | Phi = 0° | Phi = 90° | Theta = 90° |
|---------|----------|-----------|-------------|
| 3.75    | 0.69     | 7.70      | 4.01        |
| 4       | 3.63     | 7.99      | 4.77        |
| 4.25    | 4.54     | 5.05      | 4.44        |

### Table 3: Tissue layer details at 4 GHz

| Tissue Layers | Skin | Fat | Muscle | SI wall | SI content |
|---------------|------|-----|--------|---------|------------|
| Permittivity  | 40.85| 5.125| 50.82  | 50.82   | 51.63      |
| Conductivity (S/m) | 2.701 | 0.1829 | 3.015 | 3.015 | 4.622 |
| Density (kg/m³) | 1100 | 910 | 1041 | 1020 | 1020 |
was discussed on multi-layer and voxel models, in time and frequency domains in [24] and results were confirmed by measurements for male and female cases. Furthermore, the effect of the distance separating the cavity-backed antenna from body surface was assessed and analyzed in [26]. In this context, in literature, few researches were conducted to investigate the antenna performances in close proximity to lossy tissues [27–29].

The antenna safety is a primordial element to be controlled before starting measurements on real persons. This is evaluated by the Specific Absorption Rate (SAR) and compared to normalized safety guidelines. In this paper, the SAR calculations were made by means of CST calculations on a multi-layer model emulating “Normal” person case. The SAR estimations were in compliance with IEEE/IEC 62704-1 on 1 g tissue average. Both $d$ distances of 4 mm.
**Fig. 14** 3D directivity at 4 GHz of the UWB cavity-backed antenna in close proximity to human tissues for (a) Fat person $d = 30$ mm, (b) Fat person $d = 4$ mm, (c) Thin person $d = 4$ mm, (d) thin person $d = 30$ mm, (e) Navel_Voxel and (f) Back_Voxel

**Table 4** The antenna features of the cavity-backed antenna at 4 GHz using multi-layer and voxel models

| Study case          | Input impedance [Ω] | Max D [dBi] | Tot Eff [dB] | Gain [dB] |
|---------------------|---------------------|-------------|--------------|-----------|
| Thin person         |                     |             |              |           |
| (d = 4 mm)         | 53.48 − j21.19      | 10.30       | −14.53       | −4.26     |
| Fat person          |                     |             |              |           |
| (d = 4 mm)         | 54.15 − j22.08      | 10.30       | −14.54       | −4.26     |
| Fat person          |                     |             |              |           |
| (d = 30 mm)        | 59.69 + j30.50      | 8.37        | −2.95        | −5.41     |
| Thin person         |                     |             |              |           |
| (d = 30 mm)        | 62.32 + j32.49      | 8.42        | −2.95        | −5.47     |
| Navel_Voxel        | 44.99 + j 10.15     | 8.78        | −8.73        | 0.05      |
| Back_Voxel         | 29.28 + j 8.18      | 10.80       | −8.25        | 2.51      |

**Fig. 15** SAR results on 1 g average tissue according to IEEE/IEC62704-1 for (a) $d = 4$ mm and (b) $d = 30$ mm
and 30 mm were considered as illustrated in Fig. 15, revealing maximum SAR values of 0.112 W/kg and 0.005 W/kg, respectively. These results validate the antenna safety on the human body.

3.2 Measurement Results

This section deals with the measured results of the cavity-backed antenna in on-body scenarios. The measurements were conducted in an anechoic chamber at Oulu University, Finland. The SAR limit value of the proposed antenna was estimated by CST calculations using multi-layer, and the latest male and female voxel models in [24, 25], to meet the safety guidelines. The antenna matching was assessed by holding the antenna by two females at different body part positions for the “abdomen” scenario. The antennas were attached to the human subjects by elastic bands. The female subjects were wearing thin clothes, as depicted in Fig. 16, to minimize additional clothes effects. Different on-body “Abdomen” antenna positions are defined and presented in

![Fig. 16] Different antenna positions of the UWB cavity-backed antenna for “Abdomen” scenario. a Navel, b flank right, c down left, d position E, e up left, f down right, g down navel, h flank left, i position B

![Fig. 17] Measured reflection coefficient of the Low-UWB cavity-backed antenna for “Abdomen” scenario on two females a F1 and b F2

| Abdomen position | Fr [GHz] (F1/F2) | Max.S11 [dB] (F1/F2) | Bandwidth [GHz] (F1/F2) |
|------------------|------------------|----------------------|------------------------|
| Navel (A)        | 3.97/3.6         | −29.46/−24.82        | 3.39–4.6/3.20–4.07     |
| B                | 4.05/3.86        | −34.99/−29.06        | 3.77–4.43/2.95–5.63    |
| Down left        | 3.88/3.89        | −26.55/−18.29        | 3.13–5.09/2.94–4.85    |
| Down navel       | 4.02/3.89        | −26.32/−17.34        | 3.30–4.74/3.01–4.72    |
| Down right       | 3.84/4.10        | −26.46/−26.14        | 3.14–4.75/3.65–4.49    |
| E                | 4.12/4.10        | −24.63/−48.92        | 3.73–4.45/3.50–4.69    |
| Flank left       | 3.84/4.14        | −19.37/−23.49        | 3.26–6.68/3.41–5.49    |
| Flank right      | 3.87/3.88        | −17.09/−26.49        | 3.21–6.53/2.96–6.03    |
| Up left          | 4.42/3.91        | −35.10/−40.24        | 3.62–5.31/3.08–5.30    |
| Up navel         | 3.85/3.84        | −18.35/−37.01        | 2.76–4.85/2.95–5.55    |
| Up right         | 3.84/3.84        | −26.19/−41.53        | 3.17–4.88/3.01–5.35    |
real cases in Fig. 16. Since the SI tract has a curled shape, the aim of the different antenna positions is to circumvent as much as possible the abdomen area, where the SI tract could be present. This way, one can be certain regarding the good antenna matching at any chosen point of the abdomen body area.

The measured reflection coefficient results for on-body scenarios according to the antenna positions described in Fig. 16 for both female volunteers are presented in Fig. 17a, b. The measured reflection coefficient values are grouped in Table 5. It is validated that the 3.75–4.25 GHz bandwidth is covered for all the positions of the “Abdomen” area, this proves a well antenna matching in vicinity to the human body.

Next, the antenna matching experiment was focused on comparing the matching of the belly area with back area on real candidates to validate the results presented in previous section, these scenarios were known under the names “Navel” and “Back” thereafter. Measurements were conducted on a male (M4) and female (F1) and their informations are detailed in [25]. The channel propagation using two antennas on “Navel” and “Back” scenarios was investigated exhaustively as can be found in [30]. However, this paper will be restricted to show and discuss S11 and S22 results. Note that $d_s$ is the distance between the cavity edges which is assumed 0 mm when the antennas are in contact. For all the scenarios the antennas are symmetrical to the navel. Similarly, for the “Back” scenario the antennas were maintained, to some extent, in the same navel level. Figure 18a, b show the reflection coefficient result according to “Navel” scenario for M4 and F1 with different distances $d_s$, respectively. It is concluded that the resonant frequency at 3.85 GHz with − 24 dB return loss and bandwidth ($S11 < 10$ dB) of 2.84–5.6 GHz is maintained for all distances $d_s$ in the case of ‘M4’. While for F1, the bandwidth is slighty affected by the distance ($d_s$) change, however the resonant frequency is almost 4 GHz with a maximum return loss up to − 49 dB as summarized in Table 6. When it comes to the “Back” scenario for the same candidate, the difference in antenna matching results started to be noticed with the distance $d_s$ as plotted in Fig. 19 and grouped in Table 7. Similar behavior is seen from Table 8 on ‘M4’. The measurement results conducted in this sub-section are in agreement with the simulated ones using voxel model in Fig. 13b in terms of the covered 4 GHz center frequency of 500 MHz bandwidth. All these findings drive to the conclusion promoting the validity of the antenna application for the regarded BAN application i.e. Wireless Capsule Endoscopy localization at

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### Table 6 Measured reflection coefficient of the cavity-backed antenna for on-body “navel” scenario

| Navel_position (F1) | Fr [GHz] | Max.S11 [dB] | Bandwidth [GHz] |
|---------------------|---------|--------------|-----------------|
|                     | (S11/S22) | (S11/S22)    | (S11/S22)       |
| $d_s=0$ mm          | 3.96/4.10 | −46.96/−27.52 | 3.18–4.80/3.24–4.80 |
| $d_s=50$ mm         | 3.95/3.98 | −37.19/−21.01 | 3.18–4.55/3.24–4.80 |
| $d_s=80$ mm         | 4.13/3.90 | −21.12/−24.04 | 3.18–4.55/3.18–4.80 |

### Table 7 Measured reflection coefficient of the cavity-backed antenna for on-body “back” scenario on ‘F1’

| Back_position (F1) | Fr [GHz] | Max.S11 [dB] | Bandwidth [GHz] |
|--------------------|---------|--------------|-----------------|
|                     | (S11/S22) | (S11/S22)    | (S11/S22)       |
| $d_s=0$ mm         | 3.89/3.75 | −15.07/−13.91 | 3.71–4.06/3.53–4.02 |
| $d_s=50$ mm        | 3.99/3.86 | −47.03/−35.97 | 3.50–4.51/3.39–4.26 |
| $d_s=80$ mm        | 3.97/3.80 | −39.63/−22.44 | 3.56–4.43/3.15–4.43 |

### Table 8 Measured reflection coefficient of the cavity-backed antenna for on-body “back” scenario on ‘M4’

| Back_position (F1) | Fr [GHz] | Max.S11 [dB] | Bandwidth [GHz] |
|--------------------|---------|--------------|-----------------|
|                     | (S11/S22) | (S11/S22)    | (S11/S22)       |
| $d_s=0$ mm         | 4.01/4.01 | −21.47/−34.00 | 3.47–4.47/3.47–4.47 |
| $d_s=30$ mm        | 4.01/4.01 | −34.00/−34.00 | 3.47–4.47/3.47–4.47 |
| $d_s=50$ mm        | 4.01/3.96 | −34.00/−12.61 | 3.47–4.34/3.74–4.25 |
| $d_s=80$ mm        | 4.01/4.01 | −49.62/−34.00 | 2.78–6.1/3.47–4.47 |
Low-UWB range, since the required 3.25–4.25 GHz band is covered also on on-body use.

4 In-body Study

Power values using different probes were later calculated inside the multi-layer model, as described in Fig. 20. Table 9 describes the location of the power fields. The resulting values at 4 GHz are summarized in Table 10 per study case. In CST simulations, the boundary conditions were set to “Open (Add space)” in all directions, in this paper, later different boundary conditions will be tested. For \( d = 4 \) mm, the power-field probe results are decreasing in the following order: skin surface, fat1 surface, muscle surface, fat2 surface, SI wall surface, SI start surface, SI middle surface, and SI end surface at 4 GHz, for all the on-body cases as presented in Table 10. The power-field probes at skin, fat1 and muscle and fat2 surfaces reveal similar amount of power for thin and fat study cases when the antenna-skin separation distance is 4 mm. Whereas a remarkable difference is seen at SI wall surface between the person study cases. To exemplify this, the power field is \(-14.29 \text{ dB}\) for thin person against \(-23.10 \text{ dB}\) for fat person explained by the higher thickness of the lossy tissue (fat). Then the power-fields continue decreasing by quite the same dB values for thin and fat person study cases. The captured power fields for both fat and thin persons at the skin surface is around 10.20 dB for \((d = 30 \text{ mm})\) compared with 28.44 dB for \((d = 4 \text{ mm})\). This is natural since the power-field arriving to the skin are deteriorated with distance increase. At \( d = 30 \) mm, the same power absorption was observed within different layer tissues for thin and fat person cases. Consequently, it is reported from Table 8 that, the total power loss from skin to the end of SI layers is estimated 65.63 dB and 74.93 dB at \((d = 4 \text{ mm})\) for thin and fat person cases. The corresponding power values at \( d = 30 \) mm are decreased roughly by 9 dB for both cases. This slight difference can be related to the antenna radiation pattern shape and the gain. This aspect will still be investigated in coming papers using different antennas with different performances.

Next, the power absorption was estimated using voxel model from both “Navel” and “Back” sides. First, the antenna was situated in closest distance from the Navel of the voxel model, as figured in Fig. 21. Several power probes, counted to 5, are placed between different tissues starting from skin to SI layers, as encircled in blue in Fig. 21. The localized/targeted points of interest are chosen: “just before skin” referring to the first probe before reaching skin tissue, “Skin” and “Fat” tissues are associated to probes within skin and fat tissues, and “Start and End of SI” correspond to the extreme parts faced in a line of sight direction. Details for surrounding tissues are mentioned as well in the same

| E-probe          | Description                      |
|------------------|----------------------------------|
| Skin surface     | Air-skin interface               |
| Fat1 surface     | Skin-fat1 interface              |
| Muscle surface   | Fat1-muscle interface            |
| Fat2 surface     | Muscle-fat2 interface            |
| SI wall surface  | Fat2-SI_wall interface           |
| SI start surface | SI_wall-SI_content interface     |
| SI middle surface| Middle of SI_content             |
| SI end surface   | SI_content-air interface         |
Initially, assuming the normalized power value of 0 dB “Just before skin”, the power is decreased by 2 dB in skin and fat tissues, as grouped in Table 11. By arriving the SI layer, the power dropped to −12 dB. By travelling the SI layer, the power reached −29 dB. This power is less than the estimation provided using multi-layer model. This is evident since the signal would find different paths to propagate and will end by chosen the easiest using the realistic model. Later, the power values were calculated for “Back” side as illustrated in Fig. 22. This time, the probes were situated within a line starting from skin layer of the Voxel_back to the same SI segment as shown in Fig. 22. From Table 11, in skin layer the power is −2 dB which is slightly decreased to −4.8 dB in fat tissue. At muscle and bone tissues, the value becomes −17 dB and −71 dB. This sharp decrease is caused by the challenging lossy tissues. At the start of SI, the power remained roughly the same about −70 dB as at the bone tissue. This equal power level supports the idea that the signal arriving the SI has chosen a rapid path rather that passing by bone tissue. By arriving the end of SI layer, the power amount is estimated 60 dB. Ref [31] delivers a detailed comprehensive analysis for signal propagation through fat layer. It is remarkable that the average power loss from skin to SI layer in “Navel” side is lower than in “Back” side, which is due to the high tissue layers i.e. Bone and muscle faced in “Back” side besides of being the most challenging tissues for channel propagation. Ref [30] discusses the communication link between the proposed antenna and a modelled capsule antenna by providing the best position to place the on-body antenna.

| Table 10 | Power-field probe results at 4 GHz per study case using the multi-layer model | Power probes [dB] | Thin person (d=4 mm) | Fat person (d=4 mm) | Thin person (d=30 mm) | Fat person (d=30 mm) |
|----------|--------------------------------------------------------------------------------|--------------------|----------------------|---------------------|----------------------|----------------------|
|          |                                                                              | Skin surface       | 28.43                | 28.44               | 10.23                | 10.20                |
|          |                                                                              | Fat1 surface       | 26.18                | 26.18               | 8.47                 | 8.43                 |
|          |                                                                              | Muscle surface     | 7.94                 | 7.94                | −0.064               | −0.056               |
|          |                                                                              | Fat2 surface       | −2.6                 | −2.6                | −9.92                | −9.64                |
|          |                                                                              | SI wall surface    | −14.29               | −23.10              | −19.06               | −29.87               |
|          |                                                                              | SI start surface   | −15.11               | −24.08              | −19.95               | −30.48               |
|          |                                                                              | SI Middle surface  | −26.02               | −36.01              | −31.44               | −40.46               |
|          |                                                                              | SI End surface     | −37.20               | −46.49              | −41.21               | −50.75               |
|          |                                                                              | Skin-SI Total power| 65.63                | 74.93               | 51.43                | 60.95                |

| Table 11 | Power-field probe results at 4 GHz using voxel model | Power probes [dB] | Navel_Voxel | Power probes [dB] | Back_Voxel |
|----------|------------------------------------------------------|--------------------|--------------|-------------------|------------|
|          |                                                      | Just before skin  | 0            | Just before skin  | 0          |
|          |                                                      | Skin tissue       | −2           | Skin tissue       | −2         |
|          |                                                      | Fat tissue        | −4           | Fat tissue        | −4.8       |
|          |                                                      | Start of SI tissue| −12          | Muscle tissue     | −17        |
|          |                                                      | End of SI tissue  | −29          | Bone tissue       | −71        |
|          |                                                      | Skin-SI Total power| 29         | Start of SI tissue| −70        |
|          |                                                      | End of SI tissue  | −60          |                   |            |
|          |                                                      | Skin-SI Total power| 60         |                   |            |

Fig. 21 Power-field probes emplacement inside the voxel model in “Navel” side

Fig. 22 Power-field probes emplacement inside the voxel model in “Back” side
5 Conclusion and Perspectives

The paper presents the improvement of an UWB cavity-backed antenna operating at low UWB band at 3.75–4.25 GHz, defined in IEEE 802.15.6 standard for WBAN applications. The antenna is firstly built in single structure, to which a cavity was later introduced with the aim to change the main radiation and increase the antenna gain. The cavity-backed structure was assessed in on-body scenarios using a multi-layer model emulating the SI body part and completed by voxel model investigations. Different person cases named “thin” and “fat” were considered, by taking into account an antenna-skin distance of 4 mm and 30 mm. The proposed cavity-backed antenna was measured in free-space and in on-body wearable use.

The results show the suitability of the proposed cavity-backed antenna to wireless capsule endoscopy localization purposes. This is supported by the measured gain of 8 dBi with good total efficiency. The antenna performances were investigated in details in terms of impedance matching, free-space and channel propagation by using multi-layer models and latest voxel models. The impact of the antenna-skin distance in time and frequency domain using two cavity-backed antennas was presented.

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