A Wearable Multiband Monopole Antenna for Digital Television and Wireless Communications

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Abstract — A wearable multiband monopole antenna designed for digital television (DTV), commonly used communication standards including GSM 850/900, WLAN 2.4 GHz and UMTS 2.1 GHz bands and wireless sensor application bands of ISM 433 MHz and 868/915 MHz is presented. The proposed low-profile antenna was designed for operation on the human body and its performance was evaluated on different phantom types and under bending conditions. The wearable antenna is suitable for digital TV reception, wireless communication systems and sensor applications.

Index Terms—Digital TV, UHF antennas, wireless sensor networks (WSN), wearable antennas, off-body communications.

I. INTRODUCTION

Due to the rapid development of body-centric communications, currently there is an ever increasing use of wearable devices in medical, military and personal recreation application areas. Body-centric wireless communication systems require the implementation of wearable antennas because they are low profile, light weight and flexible [1]. In the literature, there is a large number of wearable antennas that have been developed mostly for frequency bands above 2 GHz [2-4]. However, there are a few wearable antennas that operate at UHF range [5-7]. These antennas are usually of large size and difficult to integrate into smart clothing [5].

Digital television (DTV) is the evolution of analog television and is rapidly spreading around the world. This development implies the need to implement antennas for DTV reception in notebooks, handheld devices, vehicles and smart clothing. The majority of these antennas are large [8], [9], complicated [10], [11] and developed on inflexible substrate, such as FR4. In [12] a novel monopole antenna is presented that covers the DTV band but not GSM, ISM or WLAN bands. A textile antenna for DTV reception was developed in [5] and was redesigned in [6] for improved bandwidth, however its size was large. A monopole DTV antenna that also covers the wireless communication standards was presented in [13] and it was also redesigned in [7], using felt substrate and Nora textile for the conducting parts.

In this paper, the monopole antenna designed in [12], was redesigned to cover DTV and WLAN 2.4 GHz bands as well as a number of wireless communication and sensor application frequencies. The antenna is designed in textile substrate in order to be easily adapted to smart clothing and implemented in wearable systems. Its operating frequency bands make this antenna applicable to sensor, DTV and body-centric communication applications. Moreover the antenna performance was evaluated on different phantoms and under bending conditions, in order to verify its proper operation in realistic situations.

II. WEARABLE ANTENNA DESIGN

The monopole FR4 antenna developed in [12] and shown in Fig. 1, covers the 530-880 MHz band for DTV reception, however for return loss < 7.5 dB.

Fig. 1. Antenna geometry.

Instead of FR4 which is an inflexible material, felt textile has been selected as the substrate of the wearable antenna. Since the impact of changing the substrate permittivity is significant on the antenna response [7], the antenna should be redesigned in order to still operate in the DTV frequency band, as the original FR4 antenna.

The felt substrate used for the antenna design has a dielectric constant of 1.4 and is 1.1 mm thick. The reflection coefficient of the antenna was optimized in free space by means of varying the parameter values of Fig. 1 using the CST Microwave Studio, until a satisfactory performance was
obtained. In Fig. 2, the final reflection coefficient of the wearable antenna in free space is depicted (dashed line). We observe that except for the DTV band, the wearable antenna now also operates in upper bands 1.96-2.24 GHz and 2.29-2.53 GHz, thus covering also WLAN/ISM 2.4 GHz.

More specifically, the resonance in the upper band at 2.4 GHz disappears for antenna distance d < 5 mm distance from the human body. However the effect is more significant for the upper band of DTV, as the antenna now shows a dual band behavior. The lower band extends from 427-970 MHz, thus except for the DTV (470-862 MHz) now also covers ISM-433 (433.05-434.8 MHz), GSM-850/900 (824-894/890-960 MHz) and WSN 868/915 (868-868.6/902-928 MHz). The upper band from 1.89 GHz to 2.54 GHz except for the WLAN/ISM 2.4 GHz band, now also includes the UMTS 2.1 (1.92-2.17 GHz) band. The parameter values of the final antenna that was redesigned for operation on the body are listed in Table I.

Fig. 2. Influence of varying the distance (d) of the wearable antenna from the body.

III. SIMULATION RESULTS

A. Antenna design on the human body

Since the antenna is intended for wearable use, as a next step, the antenna performance was evaluated for operation in proximity to the human body. The human body was modeled as a 3-layer elliptical cylinder, consisting of skin, fat and muscle tissues, as depicted in Fig. 3a. The S11 of the wearable antenna was simulated for varying distance values from the human body of 5, 10, 15 and 20 mm.

Fig. 3. The wearable antenna mounted on the three different body phantoms, a) elliptical, b) mike and c) james.

The simulation results of the antenna reflection coefficient while varying the distance from the body are displayed in Fig. 2. It can be observed, that as the antenna is moving closer to the human body, the S11 dips are shifted to the left. The lower band for DTV is slightly influenced as the distance decreases. However the effect is more significant for the upper band at 2.4 GHz. More specifically, the resonance in the upper band of 2.4 GHz disappears for antenna distance d < 10 mm from the body.

Therefore, the antenna was further redesigned for operation at 5 mm distance from the human body. After an extensive number of simulations, the S11 of the antenna mounted on the human body compared well with the antenna reflection coefficient in free space, as illustrated in Fig. 4. Actually the antenna performance on the body compared to the free space design has improved substantially especially at lower band. As observed in this figure, the antenna now shows a dual band behavior. The lower band extends from 427-970 MHz, thus except for the DTV (470-862 MHz) now also covers ISM-433 (433.05-434.8 MHz), GSM-850/900 (824-894/890-960 MHz) and WSN 868/915 (868-868.6/902-928 MHz). The upper band from 1.89 GHz to 2.54 GHz except for the WLAN/ISM 2.4 GHz band, now also includes the UMTS 2.1 (1.92-2.17 GHz) band. The parameter values of the final antenna that was redesigned for operation on the body are listed in Table I.

Fig. 4. Comparison of the simulated reflection coefficients of the wearable antenna designed in free space and the redesigned wearable antenna on phantom.

<table>
<thead>
<tr>
<th>TABLE I.</th>
<th>PARAMETERS OF THE WEARABLE ANTENNA MOUNTED ON THE BODY (IN MM)</th>
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<tbody>
<tr>
<td></td>
<td>CI</td>
</tr>
<tr>
<td>C1</td>
<td>6.5</td>
</tr>
<tr>
<td>C2</td>
<td>25</td>
</tr>
<tr>
<td>s</td>
<td>0.6</td>
</tr>
<tr>
<td>W</td>
<td>4</td>
</tr>
<tr>
<td>S1</td>
<td>115</td>
</tr>
<tr>
<td>S2</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The radiation characteristics of the antenna mounted on the body are also simulated. The radiation patterns of the wearable antenna in x-z and y-z planes for various frequencies are presented in Fig. 5. The antenna in free space is expected to have a monopole-like pattern [12]. However, when the antenna is mounted on the phantom, as observed in 2D radiation patterns in Fig. 5, the human body strongly influences back radiation (z=180°). The radiation patterns present different behavior for different frequencies especially in the y-z plane, which is expected for antennas with very wide bandwidth. Moreover three dimensional radiation patterns are also provided for the respective frequencies, in order to visualize the antenna radiation characteristics in space.
Fig. 5. Simulated radiation patterns of the wearable multiband antenna mounted on the body for various frequencies (2D and 3D patterns).

B. Impact of the body phantom

In a next step, the effect of the phantom type on the antenna response was investigated. Therefore five different body phantoms were used in order to study the impact of both the body structure and the dielectric properties. The phantoms used are: the elliptical model (Fig. 3a) in 3-layer and homogenous tissue versions, the homogenous Mike model based on a simplified approach of the human body (Fig. 3b) and finally two versions of the more detailed James model, the homogenous James and the 3-layer James (Fig. 3c). Fig. 6 shows the results of S11 for these five models. As an overall observation, the frequency bands of interest are covered in all cases, except for the ISM-433 MHz band for the case of Mike homogenous; however S11 is below -6 dB.

By comparing elliptical and James 3-layer models, one observes that there are no significant differences in the antenna response, except for a slight shift of the upper band to the right for the James model. The fact that the simplified structure used in simulations for the antenna design agrees well with the more realistic model is very important and justifies our selection. By comparing the cases of elliptical, Mike and James homogeneous models one can remark that the resonance of the Mike case is shifted upwards for the lower band bandwidth, however still covering most of the frequency bands of interest, compared to the other two models that show similar responses.

This could be attributed to the difference in body models posture, since Mike’s arms are attached to his body influencing the signal propagation, whereas James’ arms are drawn away from his torso and the elliptical model does not take into account the presence of arms. Finally, by comparing 3-layer and homogenous models for elliptical and James phantoms, it is obvious that the homogenous material results in a wider bandwidth in both bands. Therefore, the two crucial factors that influence the antenna response when mounted on the body are the arms position and the human body dielectric properties. However for practically all the phantom types all the frequency bands of interest are covered.

Fig. 6. The effect of the body phantom type and dielectric properties on S11 results.

C. Impact of bending the wearable antenna

In order to approach a more realistic situation, the antenna was tested under bending conditions while mounted on the human body. In Fig. 7 the simulated effect of bending the wearable antenna around the human torso is illustrated.

Fig. 7. The effect of bending the antenna around human torso.

As can be observed by this figure, the upper limit of the DTV band is significantly reduced to 680 MHz, while the GSM along with the 868/915 MHz bands are not covered anymore for S11<-10 dB. However, the bent antenna reflection
coefficient is below -6 dB for these frequency bands. The wearable antenna still operates in the ISM 433 MHz, lower DTV band, UMTS 2.1 GHz, and WLAN 2.4 GHz frequency bands, even under bending conditions.

D. Surface currents and radiation efficiency

The currents flowing on the antenna surface for various frequencies are shown in Fig. 8, as resulted by CST Microwave Studio. As can be seen in this figure, by inserting the bended slit and the defect ground structure (DGS) on the antenna, the path of surface current after leaving the microstrip line is meandered and therefore the electrical length of the antenna is increased. The most critical parameters for the current flow, as displayed in Fig. 8, are the width and length of the rectangle shaped DGS \((C1, C2)\), the length of the gap between antenna and ground plane \((S2)\) and the width of the slit \((S4)\). Varying their dimensions during the antenna design process had a major impact on the antenna response, confirming the above observation.

![Fig. 8. Electric currents on the antenna surface for frequencies of a) 600 MHz, b) 900 MHz, c) 2.1 GHz and d) 2.4 GHz.](image)

In Table II, the radiation efficiency values are displayed for selected frequencies in free space and on the phantom. The human body proximity has a significant influence, reducing efficiency by 92% in the lower band and 88% in the upper band.

TABLE II. EFFICIENCY OF WEARABLE ANTENNA MOUNTED ON BODY AT VARIOUS FREQUENCIES (%)

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>FREE SPACE</th>
<th>ELLIPTICAL 3-LAYER MODEL</th>
</tr>
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<tr>
<td>0.47</td>
<td>96</td>
<td>6</td>
</tr>
<tr>
<td>0.6</td>
<td>98</td>
<td>8.4</td>
</tr>
<tr>
<td>0.9</td>
<td>92</td>
<td>6.8</td>
</tr>
<tr>
<td>2.1</td>
<td>86</td>
<td>10.6</td>
</tr>
<tr>
<td>2.4</td>
<td>91</td>
<td>10.4</td>
</tr>
</tbody>
</table>

IV. WEARABLE ANTENNA MEASUREMENTS

The wearable antenna was manufactured using felt as the substrate and thin copper sheet for the patch and the ground plane and is illustrated in Fig. 9.

![Fig. 9. Wearable monopole antenna prototype (top: top view, bottom: bottom view).](image)

The antenna was attached to the back of the test subject and the reflection coefficient was measured using a vector network analyzer. In Fig. 10 both the simulation and measurement results for S11 are displayed. What can be observed is that the measurement results provide a much wider bandwidth in both lower and upper bands than that predicted from the simulation. The lower band as resulted from measurements extends from 0.38-1.24 GHz, and the upper band from 1.64-2.8 GHz thus covering all the frequency bands of interest.

![Fig. 10. Simulated and measured reflection coefficient of the antenna mounted on the body.](image)

A. Impact of body posture

In a next step, the reflection coefficient of the wearable antenna on the human body was measured for three different arbitrary postures of the test subject, in order to evaluate the antenna performance under realistic conditions. These three postures involve unselective crumpling and bending of the antenna. The S11 results are depicted in Fig. 11.

![Fig. 11. S11 results for different body postures.](image)
Fig. 11. Measured reflection coefficient of the antenna on the human body for arbitrary postures of the human body.

From Fig. 11, one can remark that for posture 1, the lower band is shifted to the right, while the lower DTV band is not included (470-685 MHz); however S11 is below -6 dB. The bandwidth of the upper band gets narrower and part of the UMTS band is not covered (1.92-1.98 GHz) however S11 is below -8 dB. By observing posture 2 results, the only change is the upward shifting of the upper band, resulting in non coverage of part of UMTS band (1.97-2.16 dB); however S11 is below -9 dB. For posture 3, a narrower bandwidth is obtained for lower band, however all bands are covered. The only band not included for this posture is UMTS band and S11 is below -7.5 dB. As a general conclusion, the crumpling and bending of the antenna because of different postures of the human body influences mainly UMTS frequency band, however in all cases S11 is below -7.5 dB for this band.

V. CONCLUSION

This paper presents a wearable multiband monopole antenna for digital television (DTV), wireless communication and sensor application bands operation. The antenna is low profile using felt substrate and thin copper sheet for the conductive parts. It demonstrated very satisfactory capabilities for operation on the human body and it is the first wearable antenna of this size to operate in the DTV band. The antenna was optimized for operation in proximity to the human body and its performance was evaluated on different phantoms and under bending conditions. The reflection coefficient measurement results agreed well with the simulations of the wearable antenna response and also showed that the antenna performed well for arbitrary user postures.

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