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Anatomical Loading on a UWB Antenna for Shoe Toe Box

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***Abstract*—A UWB 6.0-8.5 GHz monopole antenna for mounting on the toe-box area of footwear is designed using a detailed model of a running shoe and a foot-shaped phantom. Variation of anatomical features between individual people gives rise to different proximity and permittivity loads on the antenna. To take account of environment, the antenna design optimization considers different proximity distances for impact on the reflection coefficient and on the radiation efficiency.**

I. INTRODUCTION

Body Area Network is a term given to an evolving approach of linking various sensors on the human body for medical, environmental and occupational applications using wireless communications [1]. This encompasses systems with integrated sensors to analyze health indicators during normal daily activities, leisure and for rehabilitation purposes. These fascinating trends require the various research disciplines to focus on detailed analysis on the human body and the surrounding electromagnetic environments.

Physiotherapists would like to extend analysis of elderly and sporting groups beyond the clinic for certain conditions or training purposes. Reporting or recording footwear pressure sensors located between the sole of the foot and the cushioning in footwear would be enhanced with wireless links for real-time analysis and by reducing trailing wires [2]. The antenna design for such footwear telemetry is an innovative field that requires due care to balance competing pressures that include, inter alia, design resilience, size and weight reduction and power efficiency. Different challenges have to be taken in consideration, such as the ground type below the foot, different body postures, the close proximity of the shoe and of the human body, the antenna integration, etc.

The individual shapes of people's feet and various designs of footwear give rises to a range of proximities distance between a foot and an antenna placed on the upper surface of the toe-box area. Additionally, during stride this proximity can change which give rise to the need to further evaluate the corresponding variation in permittivity antennas. In this paper a monopole antenna is optimized [3] for footwear telemetry considering different proximities of the human foot. A highly detailed shoe model and an anatomical-shaped homogeneous foot are used in the simulations. The antenna is tested for different toe proximity, indicating reliable performances for all the analyzed cases.

II. MODEL DESCRIPTION

A. Antenna

A monopole antenna, designed on 0.2 mm single-sided FR4 for the 6-8.5 GHz band is shown in Fig. 1. The antenna dimensions are $W = 15.7$ mm, $L = 25.63$ mm, $W_f = 1$ mm, $S_f = 0.56$ mm, $L_g = 2.4$ mm, $H_g = 3.6$ mm, $L_{a1} = 6.17$ mm, $L_{a2} = 2.96$ mm, $L_{a3} = 2$ mm, $D = 1.47$ mm, $D_g = 3.2$ mm. The antenna is small and can be positioned easily on the toe-box of a running shoe. The free space S_{11} and the radiation patterns are stable over 6-8.5 GHz in the simulation and measurement.

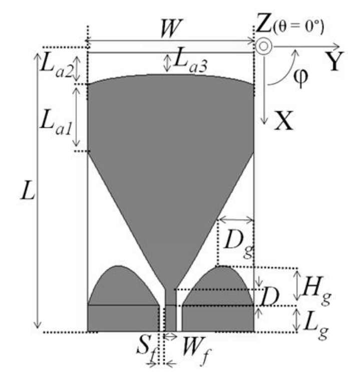

Figure 1. Monopole antenna.

B. Numerical and physical phantom and shoe model

A physical phantom is realized [4] with a dielectric permittivity equal to $2/3^{rd}$ the dielectric permittivity of the muscle. The electrical properties of the physical phantom and of a running shoe are measured [5] and used in the simulations. A 3 mm Velcro layer is used to attach the antenna to the shoe. The numerical phantom is designed with "*Make Human*" software, and imported in CST Microwave Studio® after some geometrical corrections. The numerical model of the shoe is developed using profile photographs of a real shoe and the Blender application to resolve to a 3D model. The model with the phantom is shown in Fig. 2. Three different models, shown in Fig. 3, are simulated. In the models, the foot is set at different distances within the shoe volume. Considering the top part of the big toe and the lowest Velcro point, the proximity distances are set to 8.1 mm, 3.6 mm and 1.4 mm for the Model A, Model B and Model C respectively.

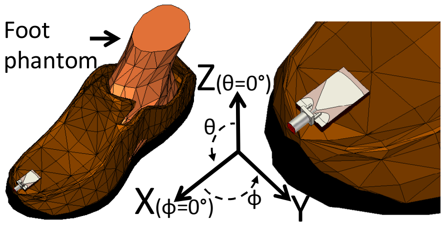

Figure 2. Monopole antenna on toe-box area.

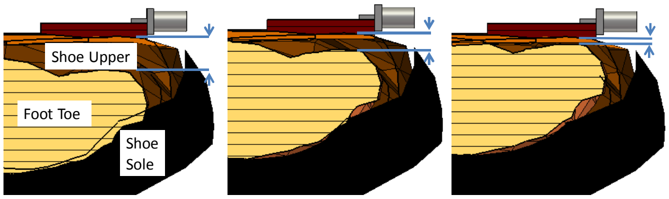

Figure 3. Cross section of shoe for Model A, Model B and Model C.

III. RESULTS AND DISCUSSION

The simulated S_{11} results reported here were validated with comparisons with Model A. The simulated results for three model configurations are shown as follows: S_{11} and radiation efficiency in Fig. 4; radiation patterns in Fig. 5 and gain characteristics in Table I.

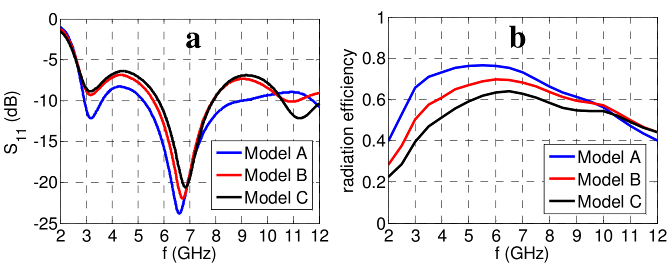

Figure 4. Simulated S_{11} (a) and Radiation Efficiency (b).

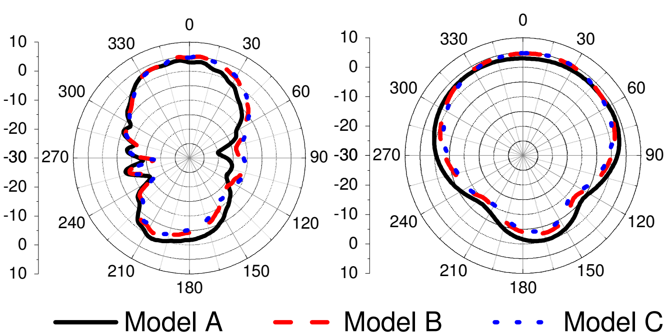

Figure 5. Simulated realized gain patterns for different antenna-toe distances at 7.25 GHz for φ=0° and φ=90°.

Inspection of figures 4.a, 4.b and 5 reveals the antenna performance is characterized by increasing reflectivity away from the foot as the proximity is reduced. The incremental change in gain is superseded by increases in directivity and the efficiency changes from 63% (Model A) to 60% (Model B) to 56% (Model C).

Considering the -7.5 dB S_{11} bandwidth, the impedance remains adequately matched for the EU-UWB bands and the variation of the antenna-foot proximity does not impair the performance. In detail, the -7.5 dB bandwidth upper limit tunes down from 12 GHz to 8.6 GHz and the -7.5 dB bandwidth lower limit goes from 2.8 GHz to 5.2 GHz.

TABLE I. REALIZED GAIN RESULTS (7.25 GHZ).

	Φ = 0°		*Φ = 90°*	
Antenna-Toe Proximity	**Peak Value [dBi]**	**Beamwidth [deg]**	**Peak Value [dBi]**	**Beamwidth [deg]**
Model A (8.1 mm)	3.9	60.7	3.6	176.7
Model B (3.6 mm)	5.2	60.6	4.8	130.3
Model C (1.4 mm)	5.1	61.0	5.0	113.6

Table 1 summaries the realized gain performance and for the worst case in the 6-8.5 GHz bandwidth, the antenna offers sufficient gain and beamwidth for upper on-body and off-body coverage of the frontal area of a person.

IV. CONCLUSION

The permittivity loading on an antenna at the toe-box area of footwear alters during a person's stride and will vary between people due to changes in anatomical characteristics and shoe fit. A UWB 6.0-8.5 GHz antenna has been designed for resilience the variability and optimized using detailed numerical models of a sport shoe and an anatomically-shaped foot. In the worst case scenario, the antenna-toe proximity is 1.4 mm and this gives rise to radiation efficiency greater than 54% and an S_{11} of -7.7 dB. The mid-frequency of 7.25 GHz has pattern beamwidth of 61° which is adequate to cover the front on-body and off-body upper areas. Similarly, off-body directions to the side are well covered with a 113.6° beamwidth. As the separation distance reduces, the realized gain increases although the radiation efficiency reduces. From inspection, the body acts as a reflector when closer to the antenna; the pattern backlobe decreases while the main lobe increases in gain. This footwear antenna type is a strong candidate for on-body coronal plane and off-body links.

ACKNOWLEDGEMENT

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