An Antenna for Footwear

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Abstract. Antenna design for footwear is an essential part of enabling reliable wireless links with lower-limb sensors used in body centric networks. Sensors can report biomechanical pressure data to analyse kinematic and posture parameters for a range of medical and sporting applications. Consideration is given to antenna shapes, the fit with shoe shapes, the positioning on the shoe and the radiation patterns suited to on body and off-body communications.

Keywords: Biomedical telemetry, body sensor networks, footwear industry, ultra wideband antennas.

1 Introduction

Intelligent footwear technologies that will report sensor information through radio links require suitable antennas to overcome adverse propagation influences near to ground level, variable tuning in close proximity to the human body and to ensure compatibility with various fabrics subject to scuffing, flexing and changing moisture conditions. Opportunities in various applications will present slightly differing antenna requirements but any approaches should take account of user influences on the designs and should avoid interfering with the user's typical stride or posture.

Around one in three older people fall each year [1] often with serious consequences including an increased likelihood of nursing home admission [2]. Every year, 10% of all older people need medical treatment following an injury and falls cause 75% of these injuries. Almost 7,000 older people were admitted to Irish hospitals with a fall in 2001 (ESRI 2001). Some recent Irish data profiled falls in an acute hospital over a one year period (Cotter et al 2006). There were 810 fall-related admissions, resulting in 8,300 acute bed days, and 6,220 rehabilitation bed days, costing €10.3 million. Fall-related readmissions resulted in 650 bed-days, bringing the total cost to €10.8 million. A typical hip fracture incident admission episode costs €14,300. The Royal College Surgeons in Ireland have shown that in frail older women, wearing their own footwear significantly improved balance compared to being barefoot with the greatest

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benefit being seen in those with the poorest balance [3]. The cause of this benefit is unclear though it may be that patients with poorer balance have deficits in foot and ankle architecture that are compensated for by footwear. Understanding the features of footwear that benefit balance in at-risk elderly individuals could lead to practical and inexpensive ways of preventing falls. In order to advance this field of research, collaboration between clinicians and engineering professionals is essential.

Future communications using miniaturised radios will enable many aspects of body-centric sensors for medical, occupational and leisure applications. Published research on wireless systems is dominated by upper-body scenarios [4]-[8] and there are many opportunities associated with extending the technology downwards to footwear. Wirelessly connected pressure sensors would dramatically enhance the clinical analysis of dynamic activities, such as gait or running in patient and sporting groups. For example, older people at risk of falls could be monitored at home or in the wider community, with a truly wireless, mobile system. This would enable detailed analysis without encumbering elderly people with wires or significantly distracting them with large devise.

Linked with other compatible technologies, they could also be the basis of new sporting performance analysis and gaming applications. For example, increased participation in endurance type activities such as marathon running, have been associated with a shift in musculoskeletal injury patterns from acute (sprains, strains, contusions, etc.) to overuse injury types. Biomechanical factors are thought to have a role in the development of these types of injuries. Antenna functionality in this particularly adverse environment for radiowave propagation has been substantially published. An appropriate balance of several competing antenna parameters will be a key requirement for communications given the adverse propagation conditions in which the devices will be expected function reliably.

Electrically small antennas radiate as a function of their close proximity surroundings. Design and performance considerations should include, inter alia, the different materials and shapes of footwear, the movement of the subject and the characteristic propagation environment. Selection of antenna positions on footwear relate to how the sensors are integrated, the resilience to material flexing and the line-of-sight visibility to the upper body or to off-body data stations. The close and varying proximity of the antenna to the ground surface beneath a foot is expected to present conditions of propagation fading. Ultra wideband (UWB) offers a suitable propagation range for body area networks and the spectrum bandwidth can offset the impact of fading loss.

2 Methodology

Computer based simulations and anechoic chamber measurements were used to evaluate how antennas would perform on the footwear. Antenna types were selected based on suitable radiation patterns at various positions on the footwear. Predictive simulations using CST Microwave Studio on a 2.40 GHz quad-core processor PC with 12 Gbytes of memory allowed researchers to evaluate performance stability. Two NVIDIA® Tesla C1026 accelerator cards were used to reduce the experimental time to around 9 hours of computational time.

A lower limb and shoe model was developed in tandem with a phantom model for measurements. The geometric features and dielectric properties were derived from the sample shoe and the homogeneous foot phantom which was constructed for the experiment.

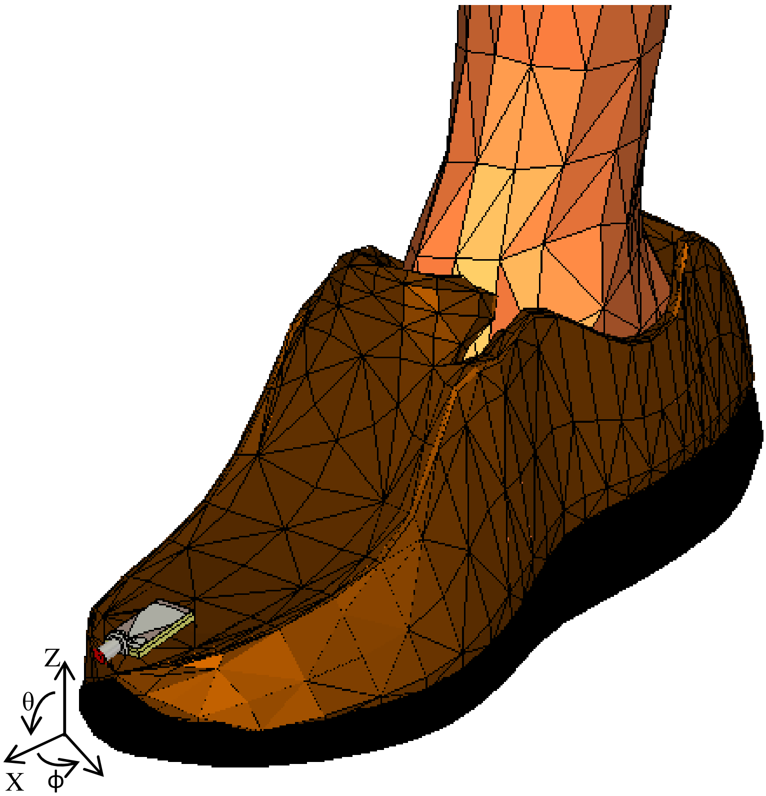


Fig. 1. CST model of foot-phantom and shoe with antenna on toe area

3 Monopole Antenna Design

A monopole antenna, in Fig. 2 comprises single-sided FR-4 dielectric with 0.2 mm thickness with an SMA feed connector. The parameters dimensions were refined for the footwear using a multi-objective algorithm to enhance a quasi-omnidirectional pattern in the 6 - 8.5 GHz band. The overall dimensions were limited $W = 15.7$ mm, $L = 25.63$ mm to minimize the overlay area on the shoe. The optimised parameters are $W_f = 1$ 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 CPW groundplane profile was refined to manage the surface currents that would otherwise impact the radiation patterns at upper frequencies.

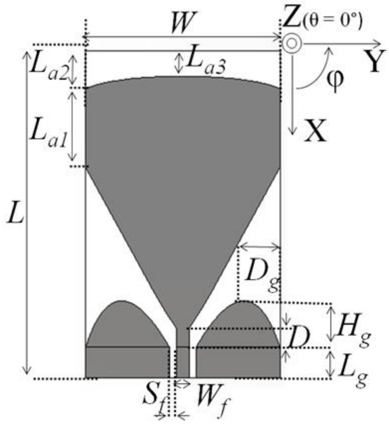


Fig. 2. Monopole Antenna

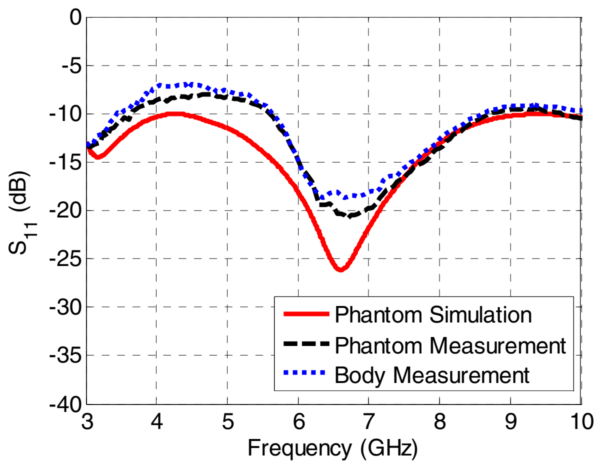
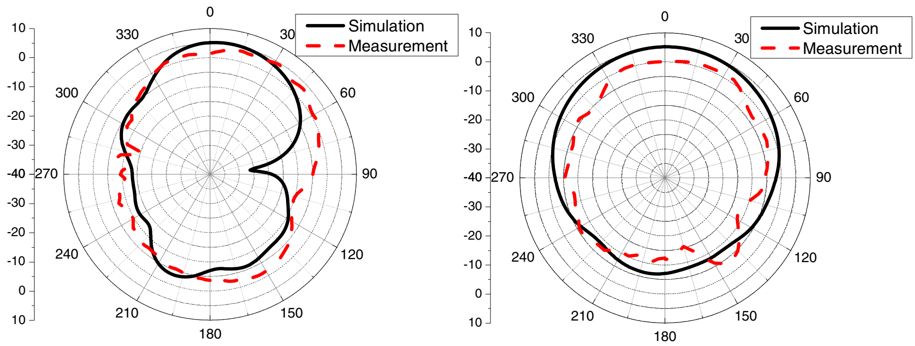
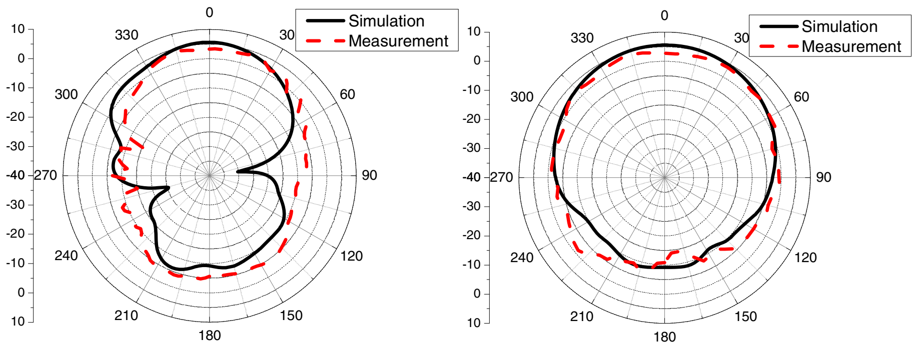


Fig. 3. S11 comparison for the material loaded monopole antenna

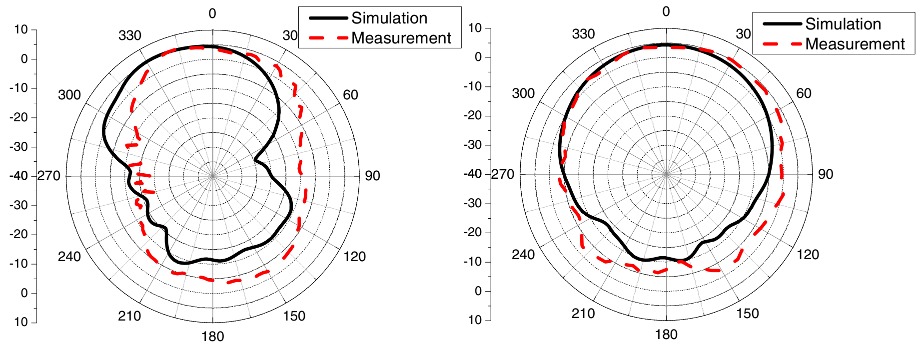
Fig. 3 shows the S_{11} achieved -10 dB match across 6 - 8.5 GHz for simulation and measurement. Comparing simulated and measured materially-loaded radiation patterns shown in Fig. 4 for the 7.5 GHz frequency indicates that the design produced a quasi-omnidirectional pattern in the $\varphi = 0°$ plane. Considering the 6 - 8.5 GHz bandwidth, the mean value of the simulated realized gain in the $\varphi = 90°$ plane ($-180° < \theta < 180°$) is greater than 1 dBi. Discrepancies in the patterns are attributed to interaction of surface currents on the measurement cable with the small ground plane.



6 GHz, ϕ = 0° plane (left), ϕ = 90° plane (right)



7.5 GHz, ϕ = 0° plane (left), ϕ = 90° plane (right)



8.5 GHz, ϕ = 0° plane (left), ϕ = 90° plane (right)

Fig. 4. Realized gain patterns (dBi) for the materially-loaded monopole antenna

The omni-directional characteristic that is characteristically exhibited in free-space changes predominantly in the back-lobe due to the presence of the shoe and the human body. While there is an approximate 3 dB reduction in the frequency-averaged realized gain in the $-180° < \theta < 180°$ plane respect to the empty shoe case, in the $90° < \theta < 90°$ the average simulated realized gain is greater than 1 dB for all the UWB frequencies.

4 Conclusion

Robust antenna performance designs are essential for sensors within wireless body area networks. Footwear mounted systems will enable real-time reporting of biomechanical parameters from ground level for sporting and medical purposes. Such short range on-body and off-body radio links can enable high-speed analysis of gait, stride and kinetic function, in addition to environmental sensing for occupational purposes.

The antenna design reported here is for the UWB 6 – 8.5 GHz frequencies on the toe area of a sports shoe. The design incorporates the influence of the footwear material properties and dielectric loading of a homogenous foot-shaped phantom. The simulation and measurement results indicate that a monopole antenna solution can provide stable performances in the UWB frequencies.

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