Investigation and Design of a Multi-band Wearable Antenna

Thomas Thalmann ^{AB1}, Zoya Popović ^{B}, Branislav M. Notaroš ^{C}, Juan R. Mosig ^{A}

^{A}*Electromagnetics and Acoustics Laboratory (LEMA), Ecole polytechnique fédérale de Lausanne*
CH-1015 Lausanne, Switzerland
[1]`thomasthalmann@gmail.com`

^{B}*Dept. of Electrical and Computer Engineering, University of Colorado at Boulder*
425 UCB, Boulder, CO, 80309-0425, USA

^{C}*Dept. of Electrical and Computer Engineering, Colorado State University*
1373 Campus Delivery, Fort Collins, CO, 80523-1373, USA

***Abstract*—In this paper, wearable antennas in close proximity of a human body are considered, focusing on portions of the frequency range between 200 MHz and 2700 MHz. In specific, non-patch type antennas with multi-band operation, light weight, easy integration with garment, low obstruction and impedances are studied. To simulate the investigated structures, an efficient surface integral equation based method is used. Several antennas are investigated under different configurations relative to the body considering the effect of the body, bending, multi-band operation, as well as fabrication and packaging options.**

***Index Terms*—Antenna, Dipole Antennas, Meander Antennas, Wire antennas, Wearable Antennas, Simulation Software, Modeling, Biological effects of electromagnetic radiation**

I. INTRODUCTION

The recent research activity in the field of wearable antennas investigates various different design approaches, including: patches [1], buttons [2], conductive fabrics [3] or combinations of such designs [4]. In this work, we consider a set of different aspects and issues related to wearable antennas in the proximity of the body, such as simple fabrication, mechanical flexibility, designs without a ground plane and scalability in operation frequency. The impact of deformation and proximity to the human body with its characteristic high and variable permittivity and conductivity [5] needs to be considered in the design. A set of desired characteristics comes from the end-user of the antenna, and some of the main properties are as follows:

- handling and using the antenna and its connection to the radio device should be as easy as possible;
- the antenna package should be tolerant to various enviromental variations and mechanical impact to a degree associated with normal use;
- the antenna needs to allow a wide range of applications which require different operating carrier frequencies;
- the antenna needs to be small, conformal, light-weight, flexible and should cause as little obstruction on the body as possible;
- as the antenna may be blocked by additional gear or clothing, the ability to move the antenna on the body is crucial;

In this work, a scalable design approach has been chosen to fulfill frequency requirements of different radio and wireless standards such as Bluetooth or Wireless LAN 801.11. In order to protect the antenna from physical impact, appropriate packaging is considered. Especially packaging that includes methods for easy re-attachment to clothing is investigated.

II. MODELING AND SIMULATION

The integration of the body in the computational model imposes specific requirements on the simulation software. The antenna has to be simulated including the nearby human tissues, which involves antenna performance aspects. The extremely difficult radiation and scattering electromagnetic problem forces the application of efficient numerical electromagnetics. Numerical techniques, such as small-domain (low-order) volume integral equation (VIE) [6] frequency techniques or low-order finite-difference time-domaine (FDTD) techniques ([7],[8]), provide an approach to model biological tissues and solve general radiation/scattering electromagnetic problems. As the structures are modeled by electrically very small geometrical elements and the field and currents over the elements are approximated by low-order basis functions, for a satisfactory accuracy a very large number of unknowns can create enormous requirements in computational resources. The search for a convenient tool led to the commercial software FEKO [9] and a surface integration equation code such as described in [10],[11],[12].

A. Large-domain method of moments modeling

The large-domain method of moments (MoM) tool for modeling of wearable antennas is based on the work described in [6], [10], [12]. It pursues the surface integral equation (SIE) approach to the analysis of metallic and dielectric structures, where both electric and magnetic surface currents are introduced over boundary surfaces between homogeneous parts of the structure, and surface integral equations based on boundary conditions for both electric and magnetic field intensity vectors are solved with current densities as unknowns. The SIEs are discretized by the higher order, large-domain MoM employing large generalized curvilinear quadrilaterals of arbitrary geometrical orders for the approximation of geometry (metallic and dielectric surfaces) and hierarchical divergence-conforming polynomial vector basis functions of arbitrary orders for the approximation of electric and magnetic surface currents within the elements. Such a combination of geometrical and current distribution approximations, which we refer to as a double-higher-order method, has shown excellent modeling capabilities and significant reductions in computational resources, while allowing complex materials, such as a human body, to be coupled with metallic antenna parts.

To enhance the functionality of the code, a Matlab framework has been created for wearable antenna applications.

Basic benchmarking of the software performance was done through simulations of a simple 2.4-GHz dipole in the proximity of a body. The body was modeled by a conical cylinder which represents the arm, of radius 4 cm to 14 cm and length 45 cm, and a uniform complex permittivity (relative permittivity 50.2, conductivity 1.9 S/m), and the antenna was placed parallel to and 1cm above the arm in air. Computation times for simulations of a simple antenna-body model indicate that the large-domain MoM is about 2 to 10 times faster than FEKO, while the results for the resonant frequency of the antenna, for example, agree within 2-5% (see Table I). In both cases, the effect of the body is a reduced resonant frequency from the case in air, typically by less than 7.5%.

TABLE I
SIMULATION COMPARISON - 2.4 GHz ANTENNA 1CM FROM ARM

Software	Simulation results		
	Computation Time	# of MoM equations	Center frequency
SIE	22min	2531	2320 MHz
FEKO	52min	2200	2337 MHz

III. ANTENNA DESIGN AND CHARACTERIZATION

In addition to the requirements listed in the Introduction, several other design goals are followed in order to reach a simple and scalable solution to a multi-band wearable antenna:

- a ground plane is not desirable. For the frequencies considered here, the wavelengths are over 10 cm in air, and the antenna would need to be relatively thick, and thus impractical. The only exception is a patch antenna, but the narrow bandwidth and pattern only in one hemisphere are not optimal.
- a light-weight and conformal design which is easily integrated with clothing implies a wire-type antenna.
- the requirement for a small size implies some type of miniaturization, while allowing for a 50 Ohm impedance.

One possible antenna which satisfies the above requirements and is the topic of this paper is the dual-band meander antenna shown in Figure 1. The longer meandered dipole is 118 mm long and is designed to be matched to 50 Ohms at 915 MHz, while the orthogonal 72 mm long smaller meandered dipole is matched to 50 Ohms at 1575 MHz.

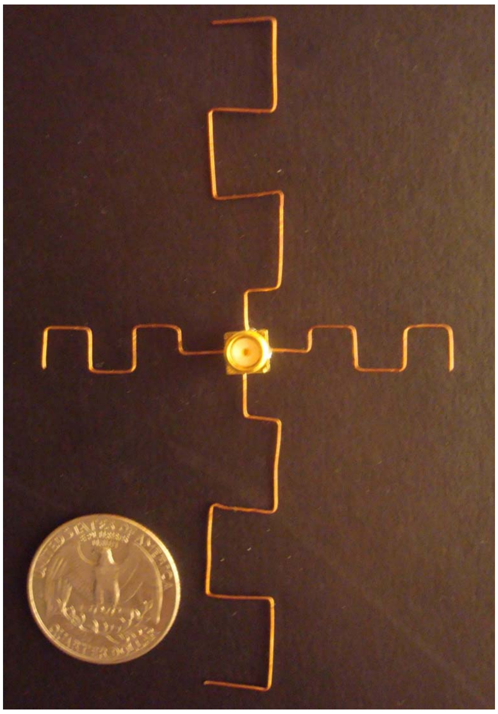

Fig. 1. Photograph of a dual-band wearable antenna prototype for 915 MHz / 1575 MHz operation with a directly-soldered single SMA feed connector. The USD 0.25 coin is shown for size.

The antenna was designed and simulated using SIE first for the two meandered dipoles separately, and then for the fabricated antenna from Figure 1. The return loss for the three cases is shown in Figure 2, and compared to the dual-band antenna measurements calibrated to the SMA connector. It can be seen that the predicted resonances are within 7% of the measured ones for both bands. The small difference in the single-dipole simulations and the dual-band antenna is an indication of the small coupling between the two arms for this orthogonal orientation, which in turn implies simplified design.

The effect of the body on such an antenna was quantified both experimentally and in simulation. The expected shift in frequency was found and is shown in Figure 3, when the antenna is placed 1cm away from an arm or a leg.

IV. PACKAGING

As the antenna will be placed on the outer layer of a person's garment, it will be exposed to physical stress and impacts. The two main types of physical impacts that were considered were torsion and bending on the one hand, as well as shock impacts on the other hand. While shock impacts are in general perpendicular to the body surface and therefore also to the

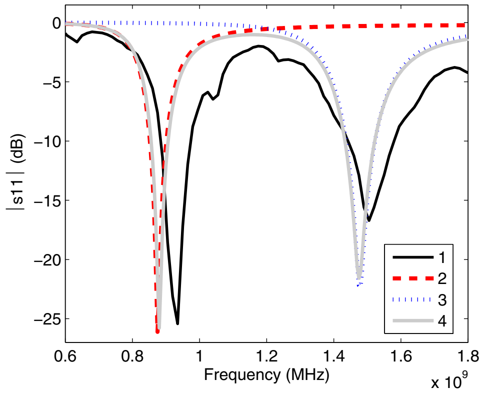

Fig. 2. Measured (1) and simulated (4) return loss of the antenna from figure 1 for a 50-ohm port and in air. The dashed lines indicated with (2) and (3) show the simulated performance of each of the two meandered dipoles separately, indicating the coupling between the two arms is small.

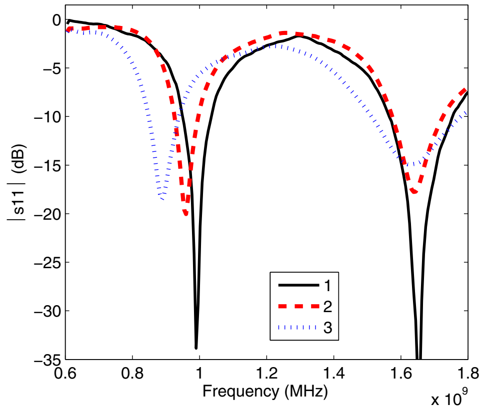

Fig. 3. Measured return loss for the dual-band antenna from Figure 1 for the following cases: (1) antenna in air; (2) parallel to an arm and 1cm above it; (3) parallel to a leg and 1 cm above it.

antenna, the relatively flat antenna will adapt to the surface and not be much affected. After an impact, the antenna needs to return to its original shape. Only a few conductive structures fulfill this requirement, and here a very thin copper thread was used due to the relatively low price, high flexibility and relatively simple fabrication process. The single-band version at center frequency around 2.4 GHz is shown in Figure 5, and was manufactured by sewing a 8-thread string of 0.2 mm diameter copper thread to a mylar foil.

Fig. 4. Wearable meander-type antenna manufactured by sewing copper thread to a plastic foil. The center frequency is around 2.4 GHz, a single copper thread is 0.2 mm in diameter, and a USD 0.25 is shown for size.

Another packaging solution that was investigated is shown in Figure 5. In this case, the antenna was encapsulated in a flexible silicone dielectric substrate for low-cost demonstration purposes as described in [13] but in a much thicker mold layer. The measured return loss is shown in Figure 6, and has an expected shift in frequency due to the permittivity of silicone, and increased loss due to the water content of the material.

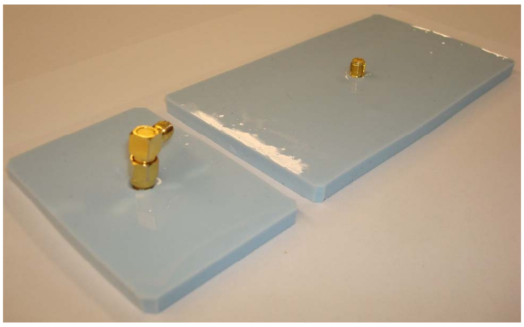

Fig. 5. Silicone molded antenna. The antennas molded are of the same type as shown on Fig.1. The mold in the front contains a 2.45 GHz and a 1575 MHz antenna, combined size 55mm x 80mm. The bigger mold in the back contains a 915 MHz and a 1575 MHz antenna of the same type, combined size 80 mm x 125 mm. The antennas are perpendicular to each other and parallel to the sides of the mold. The thickness of the mold is 6mm. The antenna plane is in the center of the mold.

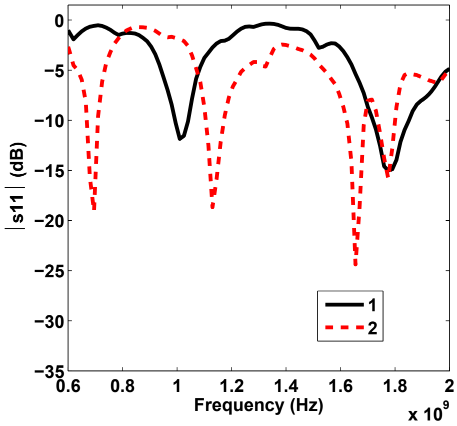

Fig. 6. A dual-band meander antenna with center frequencies at 1GHz and 1.8GHz was molded in Silicone similar as shown in Fig. 5. The measurement in air (1) clearly shows the center frequencies, whereas the measurement in silicone (2) shows higher absorption and shifts in frequency.

V. DISCUSSION

This paper presents some initial investigations related to efficient simulations and design of compact multi-band antennas in the presence of a human body and without need for a ground plane. Some packaging options are also shown as a first step to flexible and robust implementations.

There are several interesting additional properties of this type of an antenna which might be worth investigating, and are listed briefly below.

- The antenna is scalable to a certain degree to more frequency bands, by simply adding arms. One such three-band antenna is shown in Figure 7 for 915 MHz, 1575 MHz and 2400 MHz. There was no noticeable change in return loss and center frequency when the third arm was added to the design from Figure 1.
- Some additional simulations were conducted in order to estimate behavior of the antenna in different situations and configurations. The main configurations considered were: bending, with and without including a body part; different wire radii; varying number of meander elements; and varying spacing between the elements. These variations have been simulated on different types of bodies. While some conclusions can be made, e.g. that the antenna impedance changes when the arm or leg is bent, additional characterization is needed.
- Changes that result in impedance change can be compensated with simple integrated tuning networks, and this is an area of current work.
- The physical stress due body motion affects the feed in the current direct SMA connection implementation. It is of interest to investigate direct integration of chip radios at the feedpoint, as well as thin cable connections to other points on the body.
- Finally, separation of the antenna from the body by an extra layer may help in reducing absorption of electromagnetic energy by the body, and enhance reflection from the body, effectively using it as a ground plane.

VI. Conclusion

In summary, the presented design of the meandered multiband dipole makes for an easily scalable antenna. Further, the manufacturing of the antenna can be achieved with low cost and low complexity. The antenna is easy to integrate with different kinds of packaging with a focus on the feed area where physical stress is increased.

Acknowledgment

This research was accomplished within the framework of the first author's EPFL Master's thesis [14] done at the University of Colorado at Boulder, USA. The project was funded in part by Luna Innovations, Roanoke, Virginia, USA under an army SBIR, topic A072-120.

References

[1] P. Massey, "Mobile phone fabric antennas integrated within clothing," *Antennas and Propagation,11th International Conference on*, vol. 1, pp. 344–347, 2001.

[2] B. Sanz-Izquierdo, F. Huang, J. Batchelor, and M. Sobhy, "Compact antenna for WLAN on body applications," *European Microwave Conference Digest*, vol. 30, pp. 815–818, 2006.

[3] I. Locher, M. Klemm, T. Kirstein, and G. Trster, "Design and characterization of purely textile patch antennas," *IEEE Trans. Adv. Packag.*, vol. 29, pp. 777–788, 2006.

[4] P. S. Hall and Y. Hao, Eds., *Antennas and Propagation for Body-Centric Wireless Communications*. Boston / London: Artech House, 2006.

[5] S. Gabriel and C. Gabriel, "The dielectric properties of biological tissues: II. measurements in the frequency range 10 Hz to 20 GHz," *Phys.Med.Biol*, vol. 41, pp. 2251–2269, 1996.

[6] B. M. Notaros, "Surface integral equation modeling approach to the handset antenna and human body interaction," *IEEE Intern. Microwave Symposium Digest*, vol. 3, pp. 1929–1932, 2000.

[7] A. Taflove and S. C. Hagness, Eds., *Computational Electrodynamics: The Finite-Difference Time-Domain Method*. Boston / London: Artech House, 2000.

[8] S. Benkler, N. Chavannes, and N. Kuster, "Mastering conformal meshing for complex CAD-Based C-FDTD simulations," *IEEE Trans. Antennas Propagat.*, vol. 50, pp. 45–57, 2008.

[9] *FEKO comprehensive electromagnetic analysis software suite*, Suite 5.4, EM Software & Systems-S.A. (Pty) Ltd, 2007.

[10] B. Notaros, B. Popovic, J. P. Weem, R. Brown, and Z. Popovic, "Efficient large-domain MOM solutions to electrically large practical EM problems," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 151–159, Jan. 2001.

[11] M. M. Ilic and B. M. Notaros, "Higher order hierarchical curved hexahedral vector finite elements for electromagnetic modeling," *IEEE Intern. Microwave Symposium Digest*, vol. 51, pp. 1026–1033, 2003.

[12] M. Djordjevic and B. M. Notaros, "Double higher order method of moments for surface integral equation modeling of metallic and dielectric antennas and scatterers," *IEEE Trans. Antennas Propagat.*, vol. 52, pp. 2118– 2129, 2004.

[13] J. Heikkinen, T. Laine-Ma, and M. Kivikoski, "Flexible fabric-base patch antenna with protective coating," *Antennas and Propagation Society,International Symposium*, pp. 4168–4171, 2007.

[14] T. Thalmann, "Design of wearable multi-band antennas with diversity techniques," Master's thesis, EPFL-LEMA, Electrical Engineering Institute, 2008.

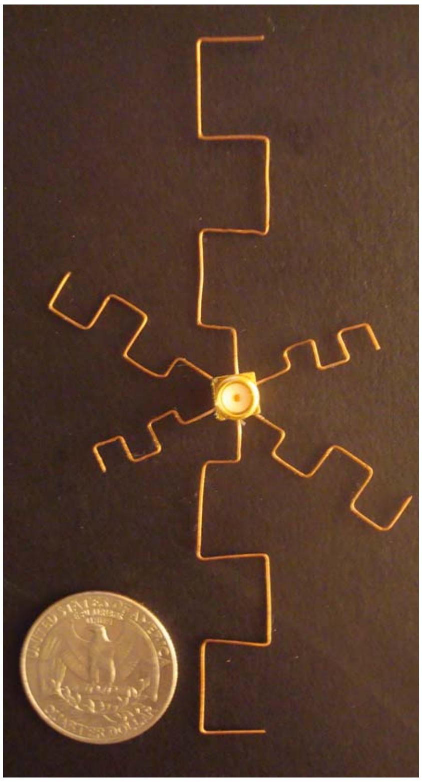

Fig. 7. A tri-band meander antenna with center frequencies at 915 MHz, 1575 MHz and 2400 MHz similar as shown in Fig. 1.