Full-Body Case Study of Wearable Magnetoinductive Waveguides

Connor Jenkins and Asimina Kiourti
ElectroScience Laboratory, Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH 43212 USA (e-mail: jenkins.1124@osu.edu)

***Abstract*—Magnetoinductive waveguides (MIWs) have previously been introduced for use in full-body, wearable applications through single- and dual-layer planar designs. MIW non-idealities that occur in the real-world, such as anatomical curvature, path bending, and clothing transitions, have been studied in isolation. Their cumulative effect has only been assessed through a full-body simulation study which identified that transmission was possible, with some limitations. In this work, we split the analysis into 1) arm-torso and 2) leg-torso to better understand the areas of a full-body system design that present design challenges. We determine that arm-torso transmission is a significant challenge for the dual-layer planar design, with a minimum loss of 8.1 dB higher than the leg-torso scenario. The single-layer planar design performs similarly for both scenarios. Finally, both designs remain viable in both presented scenarios, as also anticipated from the previous full-body results.**

Keywords— Body area networks; magnetoinductive; wearables.

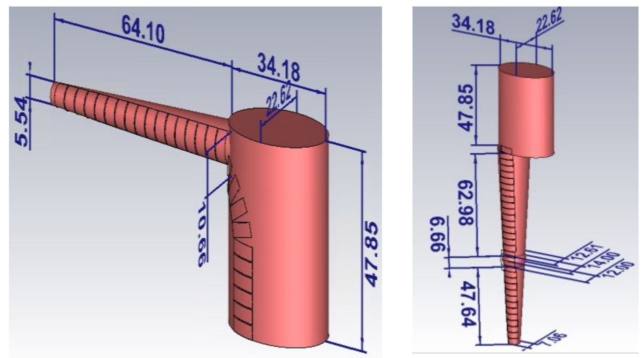
I. Introduction

We are currently developing magnetoinductive waveguide (MIW) technology for wireless body area network (WBAN) applications that overcome the state-of-the-art in terms of link budget, security, and robustness [1]. MIWs main operating principle relies on Faraday's law of induction: a series of electrically small resonant loops carry a traveling wave induced by exciting the transmit loop [2].

In previous studies, non-idealities were studied in isolation. Examples include non-uniform gaps [1], clothing transitions [4], and limited anatomical considerations [1], [3], [5]. To ensure that full-body use was possible, these non-idealities were combined in a study across an entire human model [4]. While this study confirmed full-body feasibility in the presence of non-idealities, it failed to identify the challenging areas of design for full-body applications.

In this work, we split the full-body transmission into two scenarios (arm-torso, leg-torso) to allow for more in depth analysis. We are examining the previously introduced single- and dual-layer planar designs due to their anatomical independence which is required when transmitting across the human body [3], [4]. The goal is to identify areas that require careful consideration when constructing a full-body system.

The rest of the paper is organized as follows. Section II describes the simulation setup for the two scenarios. Section III presents the transmission results for the single- and dual-layer planar designs. Section IV concludes the work.



(a) (b)

Fig. 1. Canonical human geometry models with dimensions (in cm) and MIW loops shown: (a) arm-torso model, and (b) leg-torso model.

II. Simulation Setup

Two scenarios are analyzed: 1) transmission from the wrist to the waist, and 2) transmission from the ankle to the waist. These are meant to mimic a potential real-world scenario of appendage-worn sensors communicating with a central processing hub. Fig. 1(a) shows the simulation setup for scenario 1) and Fig. 1(b) shows the simulation setup for scenario 2). While both scenarios have similar transmit distances, scenario 1) features a 27-unit MIW while the MIW in 2) has 33 units. Here, a unit refers to a single loop or two stacked and aligned loops in the single- and dual-layer cases respectively. The difference is due to the increased unit spacing present in the MIW bend in 1).

The simulations are modeled and analyzed using CST Studio Suite [6]. The human model dimensions are drawn from the averages of a large-scale survey from the United States Army [7]. The human tissue is modeled with electrical properties equal to 2/3rds of the electrical properties of muscle.

The loops of the MIW are modeled as 30 AWG copper wire. All loops are identical: 3.5 cm by 9.1 cm in length and width and loaded with a 57 pF capacitor. The individual units of the MIWs are placed 0.25 cm in the direction of propagation when possible. The distances become non-uniform for portions of the transmission due to anatomical transition and curvatures. For the dual-layer design, the second layer of loops is placed 0.1 cm above the first such that the loops of the first and second layer are exactly aligned.

The magnitude of the transmission coefficient ($|S_{21}|$) is used to analyze the transmission performance for both scenarios. The primary metrics used are the minimum loss across

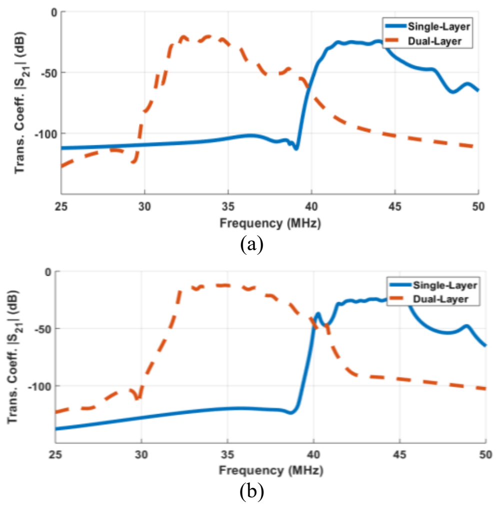


Fig. 2. Transmission coefficient results for single- and dual-layer planar MIWs placed in the: (a) arm-torso scenario, and (b) leg-torso scenario.

TABLE I
DUAL- AND SINGLE-LAYER PLANAR MIW PERFORMANCE

Transmission Setup	Dual-Layer Planar		Single-Layer Planar	
	Min. Loss (dB)	Bandwidth (MHz)	Min. Loss (dB)	Bandwidth (MHz)
Arm-Torso	20.44	3.32	24.38	3.96
Leg-Torso	12.31	5.49	24.22	4.48

frequency and 10 dB absolute bandwidth.

III. SIMULATION RESULTS

Fig. 2(a) shows the transmission performance across the arm-torso scenario. Both the single- and dual-layer designs have similar bandwidth, minimum loss, and overall behavior across frequency, barring a shift. The change in frequency is expected as explained in detail in [4]. While the dual-layer still outperforms the single-layer design in terms of loss, the gap between the two is much smaller than expected when compared to their ideal performance. This is most likely caused by the increased non-nearest neighbor effects occurring between units during the bend towards the arm on the model from the torso. Bends are primarily impacted by the change in mutual inductance between all units which can have a drastic effect on performance [8]. This impact would be unique for the single- and dual-layer designs due to their different dispersion relations and overall geometries.

Fig. 2(b) shows the leg-torso transmission performance. Here we see the strong improvement of the dual-layer design as anticipated from the ideal performance benefits along with the full-body results presented in [4]. The overall behaviors over frequency are different primarily due to the change in vertical clothing transition that occurs as the MIW transitions from the leg to the torso. Due to the “stacked” nature of the dual-layer design, the impact on performance varies significantly between the two designs, although both are robust to this effect [4].

Table I summarizes the performance for both MIWs across both scenarios. The dual-layer design outperforms the single-layer design considerably in terms of minimum loss in both scenarios but suffers from significant loss of bandwidth in the arm-torso scenario. The single-layer design has significantly less variability between scenarios, indicating that the performance loss presented by the non-idealities is more stable. In general, both designs performed worse for the arm-torso scenario than for the leg-torso scenario. This gap between the two scenarios, despite a similar transmission distance, indicates that careful design of the curved transmission path could lead to significant performance gains for the dual-layer design and, potentially, the single-layer design as well.

IV. CONCLUSION

This work builds upon previous work that highlighted the full-body viability of MIWs. By separating the study into pieces, more information is gathered regarding the design challenges for a full-body system. Overall, the arm-torso scenario led to worse performance for both the single- and dual-layer designs, despite similar transmission distances between the scenarios. Specifically, this scenario was particularly challenging for the dual-layer design, where the bandwidth dropped considerably. Performance may be increased significantly through careful design of the transmission path between the end of the arm and the torso; however anatomical limitations must be considered in the design. Future work will focus on this problem while implementing a full-body MIW system experimentally using e-textiles. This work was supported by the National Science Foundation (NSF) under grant 20053318.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation (NSF) under grant 20053318.

REFERENCES

[1] V. Mishra and A. Kiourti, “Wearable Magnetoinductive Waveguide for Low-Loss Wireless Body Area Networks,” *IEEE Trans. Antennas Propagat.*, vol. 69, no. 5, pp. 2864–2876, May 2021, doi: 10.1109/TAP.2020.3030987.

[2] E. Shamonina, V. A. Kalinin, K. H. Ringhofer, and L. Solymar, “Magnetoinductive waves in one, two, and three dimensions,” *Journal of Applied Physics*, vol. 92, no. 10, pp. 6252–6261, Nov. 2002, doi: 10.1063/1.1510945.

[3] V. Mishra and A. Kiourti, “Wearable Planar Magnetoinductive Waveguide: A Low-Loss Approach to WBANs,” *IEEE Trans. Antennas Propagat.*, vol. 69, no. 11, pp. 7278–7289, Nov. 2021, doi: 10.1109/TAP.2021.3070681.

[4] C. B. Jenkins and A. Kiourti, “Wearable Dual-Layer Planar Magnetoinductive Waveguide for Wireless Body Area Networks,” *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 8, pp. 6893–6905, Aug. 2023, doi: 10.1109/TAP.2023.3286042.

[5] V. Mishra and A. Kiourti, “Wearable Planar Magnetoinductive Waveguide WBANs: Bending Around Anatomical Curvatures,” in *2021 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (APS/URSI)*, Singapore, Singapore: IEEE, Dec. 2021, pp. 1039–1040. doi: 10.1109/APS/URSI47566.2021.9704533.

[6] Dassault Systemes, “Electromagnetic Simulation Solvers | CST Studio Suite.” https://www.3ds.com/products-services/simulia/products/cst-studio-suite/solvers/ (accessed Sep. 07, 2023).

[7] C. Gordon *et al.*, “1988 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics,” United States Army Natick Research, Devleopment and Engineering Center, Yellow Springs, OH, AD-A225 094, 1988.

[8] R. R. A. Syms and L. Solymar, “Bends in magneto-inductive waveguides,” *Metamaterials*, vol. 4, no. 4, pp. 161–169, Dec. 2010, doi: 10.1016/j.metmat.2010.05.002.