Wearable Electrically Small Loop Antennas for Monitoring Joint Kinematics: Guidelines for Optimal Frequency Selection

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***Abstract*—We have recently reported a new class of wearable electrically small loop antennas (ESLAs) that can seamlessly monitor joint kinematics (i.e., flexion and rotation). In this paper, we aim to provide generic guidelines for optimally selecting the operating frequency of such designs. Key to our approach is to first establish crucial performance benchmark criteria (i.e., received power level, angular resolution, and effect of tissue dielectric property variation). The frequency range we consider spans from the antenna mode of operation to the electrically small antenna mode (24 MHz to 1028 MHz chosen here). Based on the frequency-specific tradeoffs for each of the aforementioned performance benchmark criterion, a suitable optimal operating frequency is eventually selected (34 MHz identified as optimal in our example demonstration).**

Keywords—Electrically Small Loop Antenna (ESLA); flexion/extension; optimal frequency selection.

I. Introduction

We recently reported a new class of wearable electrically small loop antennas (ESLAs) that can seamlessly monitor joint flexion and rotation [1]. An example set-up for two ESLAs, one acting as transmitter and the other as receiver, is shown in Fig. 1. When the flexion and/or rotation angle change, the ESLAs get misaligned with respect to each other. This changes their transmission coefficient $|S_{21}|$, which can eventually be used to monitor the joint flexion angle ($_f$) and/or rotation angle ($_r$). The major benefit of this method is that it can be easily realized via e-threads, hence enabling garments for seamless motion capture in the individual's natural environment [2]. In turn, joint kinematics can be monitored in real-time and in non-contrived environments, hence overcoming shortcomings of state-of-the-art motion capture technologies. Details of the design have been reported in our previous work [1].

As would be expected, the two ESLAs shown in Fig. 1 can operate over a wide range of frequencies. Hence, selection of the optimal operating frequency for any application that a designer may have in hand becomes highly crucial. This paper is dedicated to providing guidelines for selecting the optimal frequency of operation relevant to such type of systems and for wearables working for this or similar applications.

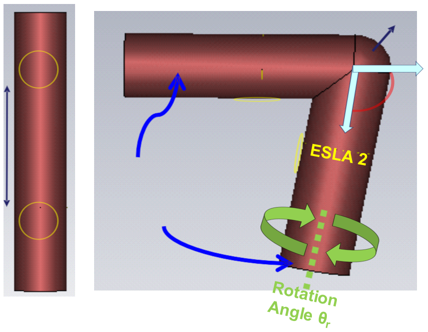

Fig. 1. Simulation set-up with cylindrical limbs and spherical joint made of 2/3 muscle as first order approximation of the human arm/leg. Both extended (left) and flexed (right) states are depicted. ESLA 1 is used as transmitter (Tx) and ESLA 2 is used as receiver (Rx).

II. Selection of Optimal Operation Frequency

There are three important performance benchmarks for the system depicted in Fig. 1, viz. received power levels, angular resolution, and tolerance to changes in tissue dielectric properties. Expectedly, these metrics change with changes in operating frequency. To identify the optimal mode of operation (ranging from antenna to electrically small antenna) or optimal operating frequency, simulations are hereafter presented using the two-ESLA simulation set-up of Fig. 1.

A. Effect on Received Power Levels

Received power levels should be as high as possible, in turn reducing power requirements on the transmitter side and improving the potential of making this technology wearable. To assess this effect, flexion and rotation simulations are performed at 24, 34, 72, 244 and 1028 MHz. The frequencies above range from the antenna mode of operation (1028 MHz is the self-resonant frequency of the employed 4-cm-radius loop) to the limits of the electrically small antenna mode. Results for $|S_{21}|$ as a function of $_f$ show that the curve corresponding to the antenna mode of operation is inconsistent. Concurrently, the antenna mode of operation is limited by line-of-sight issues and is highly susceptible to tissue property variations, making it

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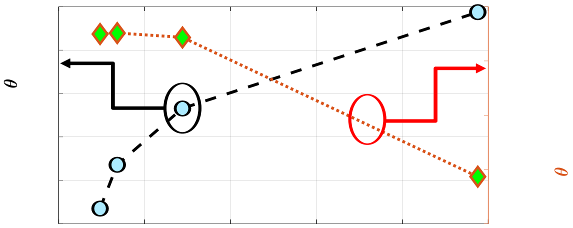


Fig. 2. Increasing $|S_{21}|$ with increase in frequency at $_f = 0^0$, as derived by the flexion curves of $|S_{21}|$ vs. $_f$ (representing received power level) (left) and variation of flexion dynamic range ($_f= 0^0$ to 100^0) with change in frequency of operation (representing angular resolution) (right).

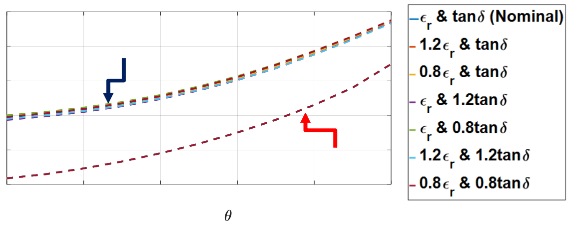
unsuitable for this application. The transmission coefficient, $|S_{21}|$, used as a measure of power reception, is plotted for all frequencies (except the antenna mode of operation, per discussion above) in Fig. 2. Here, the value of $|S_{21}|$ at full extension ($_f=0^0$) is considered as the point of least power reception among all angles. It can be clearly seen that power reception drops steeply as frequency decreases. Similar trend is observed for rotation as well. This happens mainly because of impedance mismatch with respect to 50 as the antenna size becomes electrically small.

B. *Effect on Angular Resolution*

Angular resolution should ideally be as high as possible, so that even small changes in angles can be monitored accurately. As a measure of resolution, the dynamic range of $|S_{21}|$ values corresponding to a complete range of motion (0^0 to 100^0 for flexion in our case) can be used. That is, higher dynamic ranges lead to finer discrimination of angular values, hence improving resolution. Of course, this can be done only because the curves are monotonically increasing functions. The dynamic range achieved by ESLAs operating at different frequencies is shown in Fig. 2. As seen, the dynamic range improves as we keep lowering the frequency. Because ESLAs are poor radiators, this allows us to improve the dynamic range and hence the resolution. For rotation, there is no perceptible change in dynamic range as a function of frequency. Hence, the rotational range does not play an important role in narrowing down the optimal operation frequency.

C. *Effect of Tissue Dielectric Property Variation*

The performance of the ESLA system in Fig. 1 should be ideally insensitive to changes in the underlying tissue properties. This is tested by varying the 2/3 muscle properties (relative permittivity ($_r$) and/or loss tangent (tan)) by 20% [3] at 244 MHz and 34 MHz. Results are summarized in Fig. 3. As seen, the $|S_{21}|$ performance gets impacted by tissue changes at higher frequencies, while there is almost no change at lower frequencies. This behavior is expected as in the latter case, the antenna has entered the inductive mode of operation and is no longer radiating. Similar trends are observed for the joint rotation simulations. It is important to note that the effect of tissue property changes at higher frequencies is less pronounced here as compared to wrap-around coil implementations [4] which have been demonstrated in the past to monitor flexion only. This is because in the case of wrap-around coils, relatively more radiation passes through the tissue rather than air as compared to the ESLAs described here. Hence, this system is more robust to tissue property variations as compared to the wrap-around coils reported in [4].



(b)

Fig. 3. $|S_{21}|$ versus $_f$ for 20% variation in tissue property ($_r$ and tan) at (a) 244 MHz and (b) 34 MHz.

D. *Combined Effect and Optimal Frequency Selection*

Based on the above, higher frequencies in the electrically small antenna mode are preferred for higher received power levels. However, for better resolution and to avoid susceptibility to changes in tissue properties, lower frequencies become preferable. Based on this tradeoff, 34 MHz can be selected as the optimal operating frequency.

III. Conclusion

Three performance benchmarks were selected for a joint kinematics monitoring system based on wearable ESLAs, viz. received power level, angular resolution, and effect of tissue property variation, and an optimal frequency selection procedure was demonstrated. It was found that the antenna mode of operation has to be omitted first because of its inconsistent performance, susceptibility to line-of-sight issues, and intolerance to tissue property variations. Next, higher frequencies for ESLAs were found to be better in terms of received power level, while lower frequencies were better for angular resolution and tolerance to tissue property variations. Because of this tradeoff, neither too low nor high frequencies are desired. In turn, any frequency in the deep inductive region with sufficient margin from both sides can be selected. Hence, the 34 MHz frequency was selected in our example demonstration as the optimal operating frequency. This procedure is generic and can be employed for similar designs and for any designs for wearable applications of similar nature.

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