Using Electromagnetic Properties to Detect Hydration Levels in the Human Body

Li Jiang Yan (1003693), Lim Yun Kai Clara (1003629), Loh Zhi Xuan (1003389), Low Wei Kang (1003472)

***Abstract*—Our group looked at a non-invasive method to detect hydration levels in the human body. This paper will present the motivations, the pre-existing literature with our analysis and insights.**

I. Introduction

A. Motivation

The human body is made up of 60% water [13]. As such, drinking enough water is important for personal health. A study by the US Center for Disease Control has found that nearly half of America's population is not drinking enough water [10]. Dehydration, that is, the lack of water in the human body due to not drinking enough water could cause muscle fatigue, dizziness etc [14].

Plasma osmolality is the ratio of blood solutes to water in blood plasma. When a person is dehydrated, the osmoreceptors in the body's hypothalamus detect an increase in plasma osmolality and the hypothalamus signals a release of antidiuretic hormone (ADH) into the body. ADH signals the kidneys to retain water, and that is why the color intensity of urine in blood increases when one is dehydrated. Besides this, the person will also feel thirsty as a result [11].

However, researchers caution the use of urine indices as an indication of one's hydration level [3]. The coloration of urine occurs at the late stages of the thirst reaction and as such, is not very reliable. The same goes for the feeling of thirst as well - research has also shown that old people are less sensitive to feelings of thirst [7].

Before undergoing physically demanding activities, it is important that one is sufficiently hydrated. Currently, the only reliable way to test one's hydration level is by the means of blood tests. Blood tests damage body tissue and takes a significant amount of time, so it is not a method that could be used on a regular basis. We aim to use electromagnetics to reliably test one's hydration level quickly, and the procedure should be non-invasive to the human body.

B. Classification of hydration levels

According to [3], the hydration level of an individual could be reliably detected with the concentration of sodium chloride in one's blood, [NaCl]. Table I lists how [NaCl] and one's hydration level are related.

TABLE I
Classification of Hydration Levels

[NaCl]	Less than 135 mmol/L	Between 135 mmol/L and 145 mmol/L	More than 145 mmol/L
Hydration level	Overhydrated (hyponatremia)	Hydrated (normonatremia)	Dehydrated (hypernatremia)

The authors of this paper are a group of undergraduate students from the Singapore University of Technology and Design (SUTD). This paper is submitted as part of their project (2D Designnete) for 30.102 Electromagnetics and Applications.

C. Sodium chloride concentration and electromagnetic properties

1) Relative permittivity of sodium chloride solution: The relative permittivity of sodium chloride solution, $\varepsilon_{r,\text{ NaCl}}$ is related to [NaCl] by

$$\varepsilon_{r,\text{ NaCl}} = \varepsilon_w - \alpha\,[\text{NaCl}] \tag{1}$$

given that $[\text{NaCl}] < 1.5$ mol/L (this model fits our study) [4]. Experiments in [5] suggest that $\alpha = 11.7\,(\text{mol/L})^{-1}$, $\varepsilon_w = 78.3$.

2) Conductivity of sodium chloride solution: Linear regression in [1] suggests that the conductivity of sodium chloride, σ in mS/cm is given by

$$\sigma = 0.1673\,[\text{NaCl}] + 2.3381 \tag{2}$$

The model in (2) was developed for 0 mmol/L $<$ [NaCl] $<$ 500 mmol/L (appropriate for our study) and has an R-squared value of $R^2 = 0.9926$ which implies a very strong linear correlation.

3) Relative permeability of sodium chloride solution:: The relative permeability of sodium chloride solution is independent on [NaCl]. According to CST Material Library, the relative permeability of distilled water and sea water (highly concentrated with sodium chloride) both equal to $\mu_r = 0.999991$. The change in electromagnetic properties due to the change in electrical properties in subsections I-C1, I-C2 and I-C3 would be used later in section II.

II. The Proposed Solution

A. Proposed approach

As we have seen in subsections I-C1, I-C2 and I-C3, the electromagnetic properties of sodium chloride solution changes as [NaCl] changes. We aim to use the energy from the wave generated by the transmitting (Tx) antenna received by the receiving (Rx) antenna to detect changes in the electromagnetic properties of the blood, and from that detect changes in [NaCl].

B. Device description

Figure 1 shows a simple illustration of our proposed solution. Our proposed solution consists of two rectangular microstrip patch antennas on two sides of the user's wrist. The red block shown on Figure 1 is our model for the blood inside the user's wrist. One microstrip patch antenna will be the Tx antenna whereas the other microstrip patch antenna will be the Rx antenna.

C. Design considerations

We have chosen to allow the test to be performed on the user's wrist, for the following reasons:

1) Safety: we avoided the placement of the test to be on body parts close to vital organs sensitive to electromagnetic interference (e.g. the user's heart and brain) to avoid electromagnetic interference with the functioning of these organs

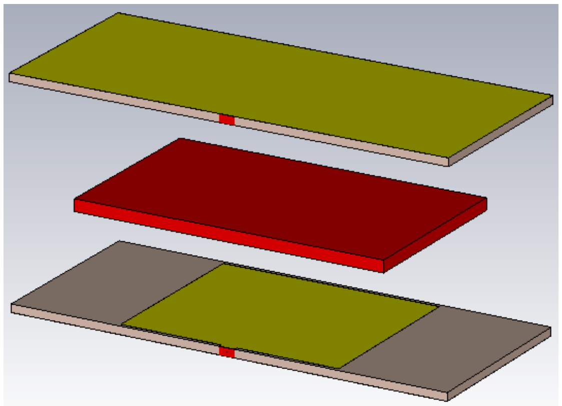

Fig. 1. Simple illustration of prototype showing a patch of blood (red) being sandwiched between two rectangular microstrip patch antennas.

2) Amount of blood: our simulations suggest that test results can be more conclusive when we test on places of the body with a good amount of blood
3) Ease of placement of device: we avoided the placement of the device on the lower body so that it would be easier for the user to use our device on upper body parts

We would also have to choose a suitable frequency range to work with, for safety reasons. The energy carried by a photon (of an electromagnetic wave) is given by $E = hf$, where h is Planck's constant and f is the frequency of the electromagnetic wave. If the frequency of the electromagnetic wave is too large, the photon's energy is sufficient to free an electron and remove it completely, ionizing the affected atom/molecule [2]. Besides ionization, electromagnetic waves would cause heating of body tissue [9].

According to the World Health Organization in [12], mobile phones which is a commonly used device operate up to 2700 MHz, and mobile phones are considered to be safe, according to [2]. As such, we decided to work with frequencies up to 2700 MHz.

D. Rectangular Microstrip Patch Antennas

The rectangular microstrip patch antennas (as shown in Figure 7) are made up of the 500 Series Copper Clad Boards milled using a PCB milling machine. For the 500 Series Copper Clad Boards, $\varepsilon_r = 4.2$, $h = 1.55$ mm, $t = 0.018$ mm (t is the thickness of the copper layer). From [8], to design a rectangular microstrip patch antenna that resonates at a frequency of f_r, L, ΔL, and W (these parameters are shown in Figure 7) are determined using (8) to (10).

For the ease of performing our simulations, these equations were entered into the parameter list of CST. This is so that we could more easily investigate how the change of a desired f_r would affect our simulation results. The rectangular microstrip patch antennas are 40 mm apart, which is the thickness of the human wrist (as measured from one of us).

E. Block of Blood in Simulations

According to [6], the diameter of ulnar arteries (arteries in the wrist) is about $d_u = 2.3$ mm. The width of the wrist (as measured from one of us) is $w_i = 60$ mm. The red block of blood in Figure 1 (our model for the blood in the user's wrist) has a height of d_u and a length of w_i. The width of the block is $L_{\text{eff}} = L + 2\Delta L$.

III. Validation

Here, we will use the following notation.

$S(f : c, f_0)$ denotes the S_{12} parameter at a frequency f, when the [NaCl] $= c$ and the rectangular microstrip patch antennas were designed for $f_r = f_0$.

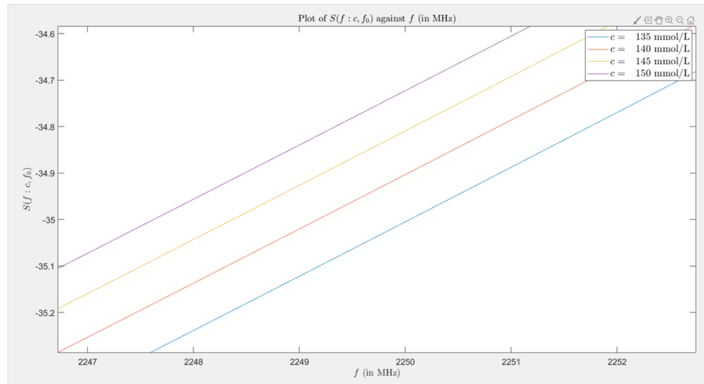

Fig. 2. A plot of $S(f : c, f_0)$ against f (in MHz) for $f_0 = 2350$ MHz at $2247 \text{ MHz} \leq f \leq 2252$ MHz

As we can see from Figure 2, at each frequency the S_{12} parameters changes for different [NaCl]. The changes are small, owing to the fact that the differences in concentrations are 0.005 mmol/L.

Besides that, as seen in Figure 3, the trend is not always consistent for all f. As such, we aim to find conditions s.t. we maximize

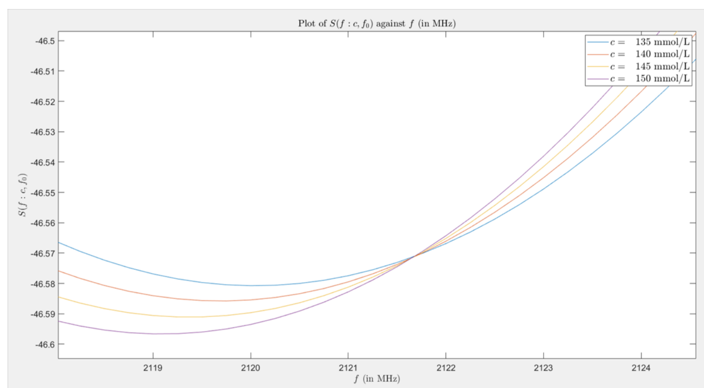

Fig. 3. A plot of $S(f : c, f_0)$ against f (in MHz) for $f_0 = 2350$ MHz at $2119 \text{ MHz} \leq f \leq 2124$ MHz

the changes of the S_{12} parameters as concentration changes and ensure that the trend is consistent for most f. We will do so with a mathematical model inspired by statistics.

We define the vector $\vec{s}(f : f_0)$ as

$$\vec{s}(f : f_0) = \begin{bmatrix} S(f : c_2, f_0) - S(f : c_1, f_0) \\ S(f : c_3, f_0) - S(f : c_2, f_0) \\ S(f : c_4, f_0) - S(f : c_3, f_0) \end{bmatrix} \tag{3}$$

Here, we will further define

$$\overline{s}(f_0) = \frac{1}{n} \sum_{i=1}^{n} \vec{s}(f_i : f_0) \tag{4}$$

$$\vec{\sigma}_s^2(f_0) = \frac{1}{n-1} \sum_{i=1}^{n} \left(\vec{s}(f_i : f_0) - \overline{s}(f_0)\right)^2 \tag{5}$$

Here, $\overline{s}(f_0)$ and $\vec{\sigma}_s(f_0)$ are the unbiased estimates of the population mean and the unbiased estimate of the population variance

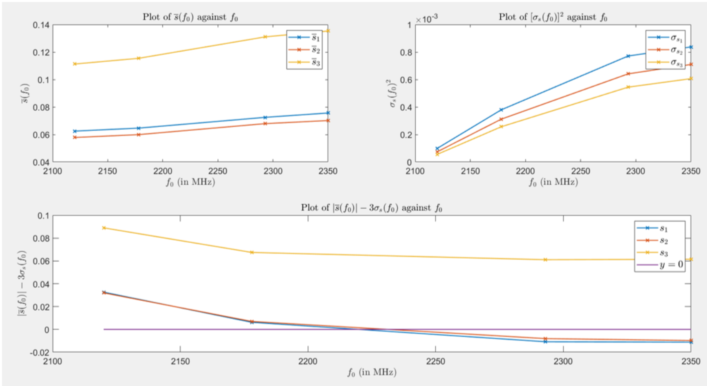

Fig. 4. A plot of different parameters (shown in graph) against f_0 (in MHz)

respectively. As shown in Figure 4, as f_0 increases, $\overline{s}\,(f_0)$ also increases. However, at the same time, $\vec{\sigma}_s\,(f_0)$ increases at a higher rate. We would like to maximize $\overline{s}\,(f_0)$ so that our test results can differentiate the S_{12} as much as possible as [NaCl] changes. At the same time, we would like to be confident that the general trend holds for most f. As such, we define our optimization problem:

$$\begin{aligned} \max \quad & \overline{s}\,(f_0) \\ \text{s.t.} \quad & |\overline{s}\,(f_0)| - 3\vec{\sigma}_s\,(f_0) > 0 \end{aligned} \tag{6}$$

The solution to the optimization problem above is $\overline{s} = \begin{bmatrix} 0.0657 & 0.0608 & 0.0564 \end{bmatrix}^{\mathrm{T}}$, where $f_0 = 2185$ MHz. Here, we constrain f_0 (in MHz) to be an integer. Figure 5 shows how $S\,(f : c, f_0)$ where $f_0 = 2185$ MHz varies with f.

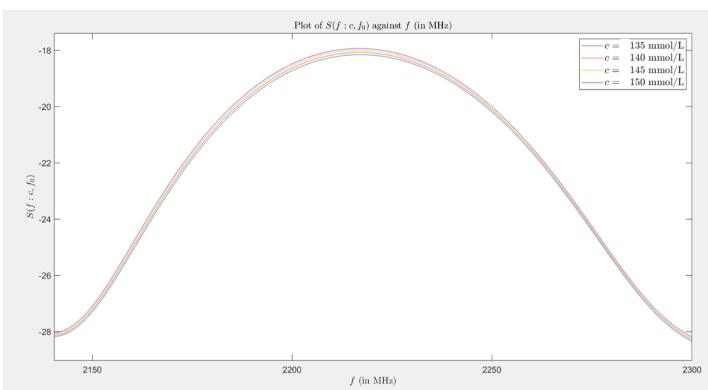

Fig. 5. A plot of $S(f : c, f_0)$ against f (in MHz) for $f_0 = 2185$ MHz at 2140 MHz $\leq f \leq$ 2300 MHz

IV. Analysis and Discussion

A. Analysis

Going further, we can break down the relationship between the concentration of NaCl and power density of the electromagnetic wave by bridging the gap between Eq 7.109 of [2],

$$\vec{S}_{av}(z) = \hat{z}\frac{|\tilde{E}(0)|^2}{2|\eta_c|}e^{-2\alpha z}\cos\left(\theta_\eta\right) \tag{7}$$

with (1) and (2). With these, we have

$$\frac{\vec{S}_{av}(z)}{|\tilde{E}(0)|^2} = \hat{z}\frac{1}{2\sqrt{\frac{\mu_r\mu_0}{\varepsilon_{r,\ \mathrm{NaCl}}\varepsilon_0}}\left(1+\left(\frac{\sigma}{\omega\varepsilon_{r,\ \mathrm{NaCl}}\varepsilon_0}\right)^2\right)^{-\frac{1}{4}}}$$

$$\exp\left\{-2\omega z\left\{\frac{\mu_r\mu_0\varepsilon_{r,\ \mathrm{NaCl}}\varepsilon_0}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_{r,\ \mathrm{NaCl}}\varepsilon_0}\right)^2}-1\right]\right\}^{\frac{1}{2}}\right\}$$

$$\cos\left[\frac{1}{2}\tan^{-1}\left(\frac{\sigma}{\omega\varepsilon_{r,\ \mathrm{NaCl}}\varepsilon_0}\right)\right]$$

For the relevant derivation, please refer to the appendix. We differentiated this equation w.r.t. to [NaCl] but achieve a rather long equation which was impossible to analyze so we decided used graphical methods to observe the correlation in between the power density and [NaCl].

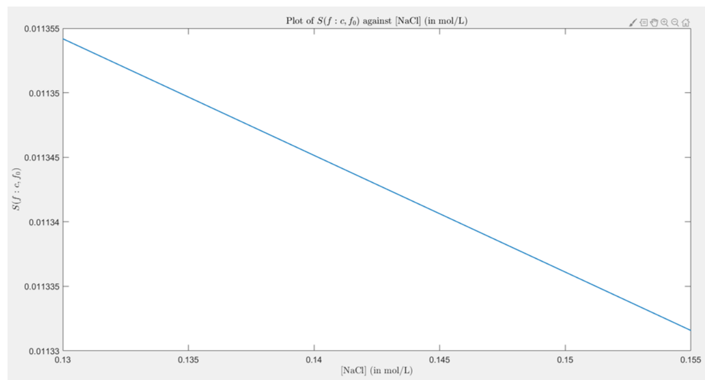

Fig. 6. A plot of $S(f : c, f_0)$ against f (in MHz) for $f_0 = 2185$ MHz at 2140 MHz $\leq f \leq$ 2300 MHz

Over the range of $c = [0.135, 150]$, we can see from Figure 6 that there is a downwards slope, this reinforces the literature that salt concentration can be detected physically through antennas. However the range of power transferred is quite small at the 10^{-2} range. The antennas that we can build for this level of precision is confined by the school's equipment and our current understanding. Further research could go into the other levels of resonance in and how they may be affected by levels of hydration in the system. Such examples are plasma and bone marrow.

B. Discussion

Besides being able to be used to test one's hydration level, our proposed device could also be used as a method to do quantitative chemical tests without the using chemical reactants and without consuming the chemical tested.

V. Conclusion

In conclusion, we proposed a method to determine the level of hydration in the human body by non-invasive electromagnetic methods (section II).

Using CST Microwave Studio, we have shown the the changes in hydration level could possibly be determined by simple measurements of S-parameters (section III) which reflect the change in electromagnetic properties of blood model. Afterwards, we have also used a mathematical model to determine the best conditions for our prototype (set $f_r = 2185$ MHz, section III).

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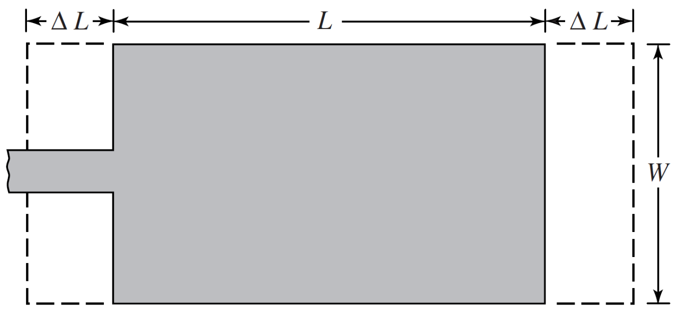
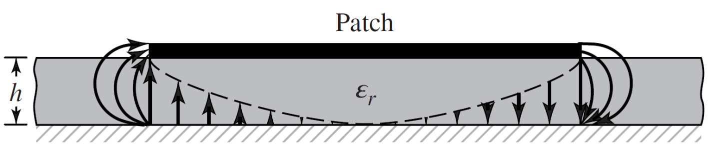
APPENDIX

Rectangular microstrip patch antenna



(a) Top view



(b) Side view

Fig. 7. Physical and effective lengths of rectangular microstrip patch. Image obtained from [8].

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{8}$$

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{\text{reff}} + 0.3)\,(W/h + 0.264)}{(\varepsilon_{\text{reff}} - 0.258)\,(W/h + 0.8)} \tag{9}$$

$$W = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{10}$$

where v_0 is the speed of light in vacuum.

Statistical methods

According to statistics, for a normally distributed rv $X \sim N\left(\mu, \sigma^2\right)$ where μ denotes the mean and σ denotes the standard deviation (or positive square root of the variance),

$$P\left(\mu - \sigma \le X \le \mu + \sigma\right) = 0.6827$$
$$P\left(\mu - 2\sigma \le X \le \mu + 2\sigma\right) = 0.9545$$
$$P\left(\mu - 3\sigma \le X \le \mu + 3\sigma\right) = 0.9973$$

This is known as the 68-95-99.7 rule [15]. For our model, we assume that the distribution of $\vec{s}\,(f : f_0)$ will have identical properties. Since $0.9973 \approx 1$, we are quite confident that by constraining either

$$0 < \overline{s}\left(f_0\right) - 3\vec{\sigma}_s\left(f_0\right) \le \overline{s}\left(f_0\right) + 3\vec{\sigma}_s\left(f_0\right) \tag{11}$$

or

$$\overline{s}\left(f_0\right) - 3\vec{\sigma}_s\left(f_0\right) \le \overline{s}\left(f_0\right) + 3\vec{\sigma}_s\left(f_0\right) < 0 \tag{12}$$

for most of the time, we will get consistent trend of $S\left(f : c, f_0\right)$ values. These two conditions can be expressed in the constraint in (6).

Derivation of power density equation

The complex intrinsic impedance is given by

$$\eta_c = \sqrt{\frac{\mu}{\varepsilon'}}\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)^{-\frac{1}{2}} \tag{13}$$

With the real and imaginary parts of permittivity being $\varepsilon' = \varepsilon$ and $\varepsilon'' = \sigma/\omega$ respectively, we get

$$\eta_c = \sqrt{\frac{\mu}{\varepsilon}}\left(1 - j\frac{\sigma}{\omega\varepsilon}\right)^{-\frac{1}{2}} \tag{14}$$

The attenuation constant

$$\alpha = \omega\left[\frac{\mu\varepsilon'}{2}\left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)\right]^{\frac{1}{2}} \tag{15}$$

With $\varepsilon = \varepsilon_{r,\ \text{NaCl}}\varepsilon_0$ and $\mu = \mu_r\mu_0$,

$$\eta_c = \sqrt{\frac{\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}{\mu_r\mu_0}}\left(1 - j\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)^{-\frac{1}{2}} \tag{16}$$

$$\alpha = \omega\left\{\frac{\varepsilon_{r,\ \text{NaCl}}\varepsilon_0\mu_r\mu_0}{2}\left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)^2} - 1\right]\right\}^{-\frac{1}{2}} \tag{17}$$

Expressing η_c in polar form, we have the following expression:

$$\begin{aligned}\eta_c &= \sqrt{\frac{\mu_r\mu_0}{\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}} \\ &\quad\left\{\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)^2}\exp\left[j\tan^{-1}\left(-\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)\right]\right\}^{-\frac{1}{2}} \\ &= \sqrt{\frac{\mu_r\mu_0}{\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}}\left(1 + \left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)^2\right)^{-\frac{1}{4}} \\ &\quad\exp\left[\frac{j}{2}\tan^{-1}\left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)\right]\end{aligned}$$

Substituting the above into (7),

$$\begin{aligned}\frac{\vec{S}_{av}\left(z\right)}{|\tilde{E}(0)|^2} &= \hat{z}\frac{1}{2\sqrt{\frac{\mu_r\mu_0}{\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}}\left(1 + \left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)^2\right)^{-\frac{1}{4}}} \\ &\exp\left\{-2\omega z\left\{\frac{\mu_r\mu_0\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}{2}\left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)^2} - 1\right]\right\}^{\frac{1}{2}}\right\} \\ &\cos\left[\frac{1}{2}\tan^{-1}\left(\frac{\sigma}{\omega\varepsilon_{r,\ \text{NaCl}}\varepsilon_0}\right)\right]\end{aligned}$$

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Team Members:

Li Jiang Yan is an undergraduate student of SUTD, taking the Electrical Engineering (EE) track of the Engineering Product Development (EPD) program. His strengths and interests include circuit design and applied mathematics.

Lim Yun Kai Clara is an SUTD undergraduate student in the EPD Robotics track. Her interests include machine learning and bionics.

Loh Zhi Xuan is an undergraduate student of SUTD, taking the self-directed track. His strengths include programming and CADing and his passion lies in making useful things to make people's lives easier.

Low Wei Kang is an undergraduate student of SUTD. His strength and interest is in applied math.