PICC, Polarization and Impedance Controlled Car

A Proposal for the 2024 IEEE AP-S Student Design Contest

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I. Introduction

WORK hard, play hard, or do both at the same time? We present a way to play with your Radio-controlled car while learning the concepts of polarizing waves and impedance matching.

While most students read about polarization and impedance in their undergraduate electromagnetics courses, most never get to experience the phenomenon in action. With this project, students will have the polarization in their hand, and the impedance matching in front of them. We present the Polarization and Impedance Controlled Car, abbreviated as PICC. The setup is a unique way of experiencing the concepts and it can be set up for demonstration in minutes.

In short, a signal will be transmitted from one hand to the other using an antenna, and the amount of reflection back to the antenna will vary based on the relative distance and angle between the hands. The two control parameters, distance and rotation angle between the hands will control the acceleration and direction respectively. It could also be used for further applications that require two parameters to control a system or device.

A. Background

Electromagnetic waves can be characterized by the oscillation of electric and magnetic fields. Polarization indicates the orientation of the electric field — one common basis typically used in antenna application is vertical or horizontal [1]. The observer, in linear polarization also has to be aligned, an x-directed antenna will not observe an y-oscillating wave. Two orthogonal waves out of phase creates left/right circular waves commonly used in space applications [2]. They contain the orthogonal waves as basis. For the PICC project a linearly polarized patch antenna will be used , also commonly used by mobile phones and CubeSat antennas [3].

If a wave impinges on a strip grid consisting of parallel metal strips, the angle between the grid and the direction of polarization determines how much is reflected. When the grid is parallel to the polarization we observe maximum reflection and when they are orthogonal a minima. The angle of the grid determines which polarizations are reflected and which are not.

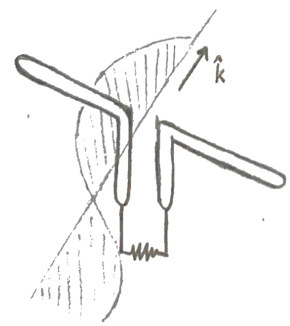

Figure 1: A dipole antenna where $\hat{k}$ is the direction of propagation.

A simple straight dipole antenna will transmit electromagnetic waves that propagate radially outwards from it as any other antenna in the far-field. The wave is polarized in the direction of the oscillations, see Figure 1. Antenna impedance is the opposition of alternating current flow. This can be measured by a device called a Vector Network Analyser, or VNA for short. A NanoVNA is a compact and accessible form of a VNA. The smaller size and reasonable price makes it suitable for on-body applications for university or high school students.

The S11 parameter also known as the reflection coefficient measures how much voltage from the antenna is reflected. If S11 is equal to one all voltage is reflected, if S11 is zero none of the voltage is reflected back. If we have two antennas we can also measure the transmission coefficient S12 which is the voltage received at antenna 2 relative to how much voltage is sent out from antenna 1.

The design of antennas is crucial for them to function effectively, with various factors coming into play. First of all it is important that an antenna is of resonant-length, meaning that the length of an antenna, L should be around half a wavelength $\lambda/2$. As we can see in the following equation;

$$L \approx \frac{c_0}{2f\sqrt{\epsilon_r}}, \quad \lambda = \frac{c_0}{f}. \tag{1}$$

where ϵ_r is the relative permittivity of the dielectric layer situated between the ground plane and the patch antennas, f the radiated frequency and c_0 the speed of light in vacuum [4]. Other important factors are the width, shape, spacing and arrangement of antennas. The shape of the antenna, including width and length, affects the input impedance, bandwidth and the radiation pattern [5]. Lastly, the spacing and arrangements of multiple antennas is decisive for the direction and beamwidth [6, p. 40] of the waves [6, p. 41].

II. Design and Setup

The PICC is compromised of a few different parts. On one hand an antenna will be attached and on the other a strip grid made of metal, as visualised in Figure 2. The idea is that the palms are placed facing each other and by changing their relative distance and rotation the impedance of the antennas is influenced. The impedance change will be measured by a NanoVNA, then processed by a Raspberry Pi to control an RC car.

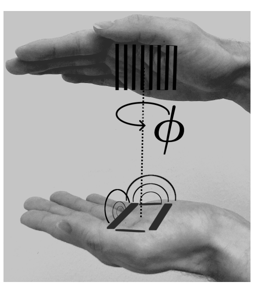

Figure 2: Overview of Design, the transmitting antenna is attached to the lower hand and the reflecting strip grid to the upper hand. ϕ is the relative angle of the two hands.

A. Antenna design

The chosen frequency for the antennas is $3.0\,\mathrm{GHz}$. Higher frequency reduces the size of the design overall as antenna size is naturally described in wavelengths. The selected frequency ensures that the antennas are appropriately sized relative to the dimensions of a hand.

A set of four antenna elements are placed in a square shaped formation on a substrate with $\epsilon_r = 4$ and a thickness of $1.5\,\mathrm{mm}$. On the bottom of the substrate there is a conducting ground plane. Two parallel antennas on opposing sides of the substrate, for example a_1 and a_2 as seen in Figure 3, are seen as a pair. Same goes for b_1 and b_2. The two pairs will be connected to one port each of the NanoVNA. Each pair is effectively a stronger antenna at the center of the square [6, p. 286]. A cross of antennas would have resulted in disturbances and problems, hence why this design was chosen instead. The dimensions illustrated in Figure 3 have been calculated using Equation 1 to be: $\lambda/2 = 5.0\,\mathrm{cm}$, $L = 2.5\,\mathrm{cm}$. The antenna width w has been chosen to be $0.15L$, as this is small enough to avoid overlapping or disturbances from other elements. The thicker dots in the illustration represent the location of the antenna ports which are shifted about $d = 0.06L$ away from the centre. This small correction is done to match the impedance of the antenna with the connected cables at $50\,\Omega$.

Note that while using a ground plane, the antennas are essentially isolated from the body, this is done mainly to simplify the simulations but may be altered for the final design.

On the opposing hand, the strip grid will consist of a square of parallel metal strips as shown in Figure 2. The preliminary size of the grid covers the area of the antennas, see Figure 4. The grid including its dimensions are illustrated in Figure 3 with eight strips but in the simulations below a number of thirteen strips was used.

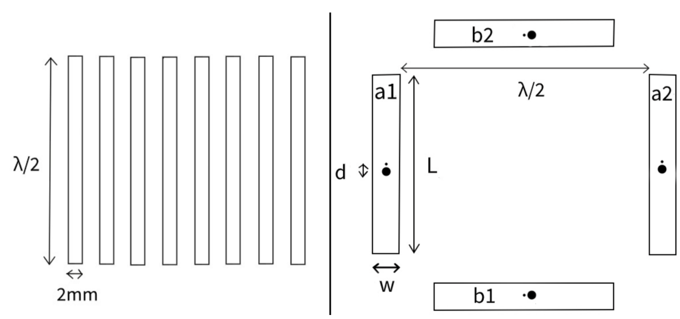

Figure 3: The patch antenna consisting of a pair of parallel-coupled antennas over a common ground plane to the right and the strip grid design to the left.

The antennas and the strip grid will give different values of S11 and S22 for the two antenna pairs respectively. This will depend on the distance between the hands and the angle ϕ between hands. The sum of the reflection coefficients S11 and S22 will be varied depending on the distance and will be used as the throttle signal i.e. the minimum for the sum of reflection coefficients. The sum is used to get a distance measure even when angles are at 0 or 90. Changing the angle ϕ changes the ratio between S11 and S22. For $\phi = 45°$ both pairs will theoretically reflect the same amount and result in the ratio between S11 and S22 being equal to 1. For $\phi = 0°$ and $\phi = 90°$ the ratio will tend to 0 or ∞.

B. *Signal processing and car control*

To control the RC car using the NanoVNA, the impedance data is processed by a Raspberry Pi (RPi) and sent to the car's controller. Throttle control is determined by the sum of s11 and s22 parameters, with thresholds set for 'full gas' and 'no gas.' The direction is controlled by the ratio between S parameters, scaled to a max/min angle range. Signal processing ensures a linear interface for the student operating the PICC, converting measurements to match joystick output signals. The modified off-the-shelf radio controller receives signals from the RPi instead of the analog joystick.

C. *Simulations*

We conducted simulations using commercial software to demonstrate that the antenna and its corresponding strip grid can provide accurate information for controlling an RC car effectively. The antenna far-field radiation pattern as well as the S-parameters for various distances and rotations were simulated with *Feko 2023*. For the simulations the hands and other environmental disturbances are not included as they would greatly increase computation time and make it harder to draw conclusions from the data. In the simulation the pairs of antennas are connected using a non-radiating network, in reality they would be connected using coaxial cables. The simplified version of the antenna and the corresponding strip grid used in *Feko* can be seen in Figure 4.

We simulated the antenna without any strip grid to get a baseline reflection coefficient for the antenna and determine the optimal placing of the point feed for the antennas, the baseline S11 and S22 is seen in Figure 5. We see a dip of around $-40\,\mathrm{dB}$ at the resonant frequency of $2.984\,\mathrm{GHz}$ for antenna a and $2.991\,\mathrm{GHz}$ for antenna b, which is nearly perfectly matched.

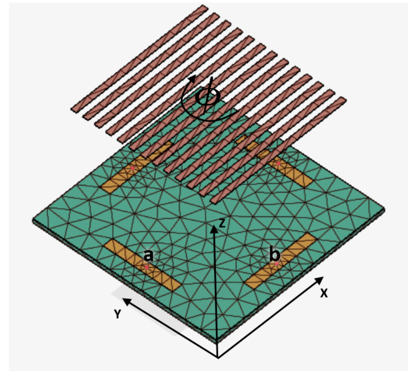

Figure 4: Geometry of the model in *FEKO*.

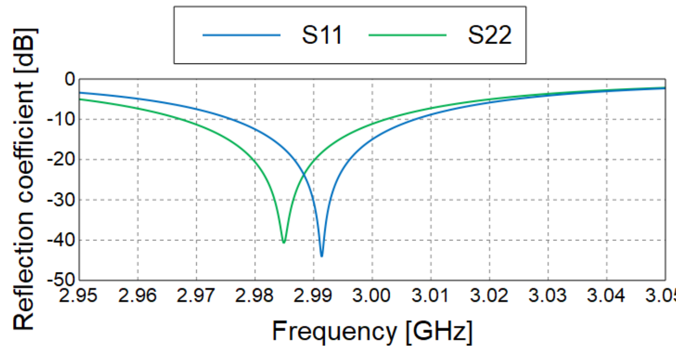

Figure 5: Reflection coefficient in dB from 2.9-$3.05\,\mathrm{GHz}$

To show the interference effect of the $\frac{\lambda}{2}$ spacing of the antenna elements we also did a polar plot of the far-field directivity in Z direction at $\phi = 0°$ and $\phi = 45°$, shown in Figure 6. This shows that maximum gain in the normal direction of the plane has been achieved.

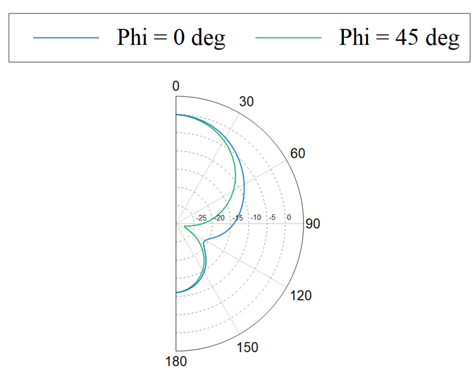

Figure 6: Directivity of antenna in dB at $\phi = 0°$ and $\phi = 45°$.

To determine the effect of the strip grid on the antenna at different positions we simulated S11 and S22 at the distance $1\,\mathrm{cm}$ to $15\,\mathrm{cm}$ from the patch as well as the angle $\phi = 0°$ to $\phi = 90°$ from antenna a. In Figure 7 we can see how distance affects the sum of S11 and S22 at their respective resonant frequency. This was done at three different angels to show that the sum of S11 and S22 can be used as a measure of distance irrespective of rotation, indeed at these three angles the sum of S11 and S22 is almost the same. Up to about $5\,\mathrm{cm}$ all sums seem to decrease, above this distance the relationship between distance and impedance becomes more complicated. In order to determine distance greater than $5\,\mathrm{cm}$ we could also use the phase information from the nanoVNA to get a better prediction of distance. Since the relation between distance and s-parameter seems to be non-linear, the signal processing will have to compensate for this to ease controlling.

In Figure 8 we see that as we rotate the patch from $\phi = 0°$ to $\phi = 90°$ the real part of S11 decreases and the real part of S22 increases in a sinusoidal way, thus we should be able to use inverse trigonometric functions to determine ϕ from S11 and S22.

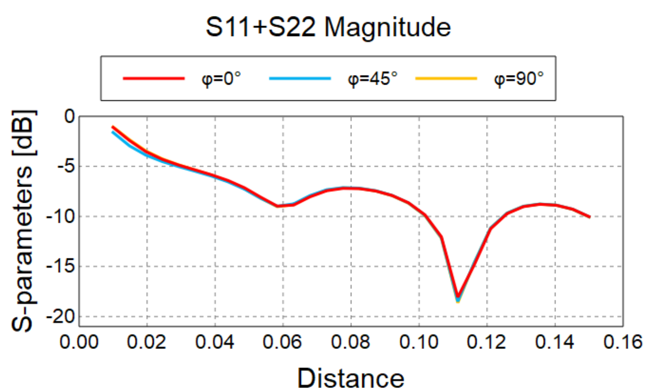

Figure 7: The magnitude of the (complex) sum of S11 and S22 in dB with distance to the patch on the x-axis.

III. Conclusion

In conclusion, polarization and impedance are important parts of electromagnetics and using antennas they can be clearly demonstrated to students. The PICC uses a pair of two parallel-coupled antennas and a strip grid of metal mounted on the hands enabling a unique and educational way to control two parameters by altering the position of the hands. The simulations done in this project show that for different relative angles ϕ and distances between

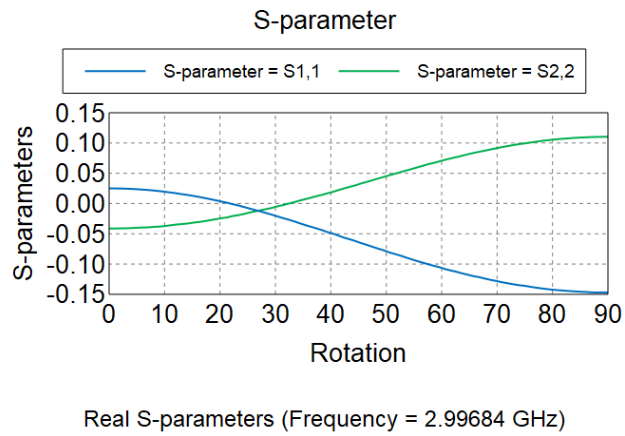

Figure 8: Change in S11 and S22 parameters near their respective resonant frequencies with the relative angle ϕ on the x-axis. Distance to patch is $5\,\mathrm{cm}$.

hands the impedance values change as expected, consequently showing feasibility to use antennas for this purpose. The PICC enables the student to feel and interact with the waves, creating a deeper understanding. Next steps will be to construct the hardware, write software, conduct real world tests and adjust the system for differences unaccounted for in simulations.

IV. Bill of Materials

In table I one can view the preliminary bill of materials. For some products we have converted the price in SEK to USD using the convertion rate: 1 SEK = 0.098 USD. This gives the total cost 650 USD. To anticipate for unexpected rise in cost we have added additional 20% to the total cost, making a total of 800 USD.

Table I: Proposed bill of the materials needed to build our project. (*) est. cost, depends on shipping and design.

Items:	Price:	Source:
RC car and controller	$30	Biltema [7]
nanoVNA V2 Plus4 pro	$400	Tindie [8]
Raspberry Pi 4b	$110	Kjell & Company [9]
Micro SD card 64 GB	$30	Kjell & Company [10]
Patch Antenna (PCB)	$20	PCBWay [11]
Strip grid (PCB)	$20	PCBWay [11]
Breakout board, GPIO cables, etc	$30	Kjell & Company [12]
hook-and-loop tape	$10	Biltema [13]
Total:	$650	
Total + 20%:	$800	

ACKNOWLEDGMENT

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LETTER FROM MENTOR

(Attached below)

REFERENCES

[1] D. J. Griffiths, *Introduction to Electrodynamics*. Pearson, 2013.

[2] L. Boccia and O. Breinbjerg, *Antenna Basics*. John Wiley Sons, Ltd, 2012, ch. 1, pp. 1–35.

[3] "Circular and linear polarization of vsat antennas," Feb 2022, (Last visited 2023-12-20). [Online]. Available: https://www.linksystems-uk.com/circular-linear-polarization/

[4] "Microstrip (patch) antennas." [Online]. Available: https://www.antenna-theory.com/antennas/patches/antenna.php

[5] P. Salonen, M. Keskilammi, and Y. Rahmat-Samii, "Textile antennas: Effect of antenna bending on radiation pattern and efficiency," in *2008 IEEE Antennas and Propagation Society International Symposium*, 2008, pp. 1–4.

[6] C. A. Balanis, *Antenna theory*, 4th ed. Hoboken, NJ: Wiley-Blackwell, Jan. 2016.

[7] Biltema, "Rc snurrbil, 2,4 ghz," (Last visited 2023-12-15). [Online]. Available: https://www.biltema.se/fritid/leksaker/radiostyrda-leksaker/rc-snurrbil-24-ghz-2000037918

[8] Tindie, "Nanovna v2 plus4 pro," (Last visited 2023-12-15). [Online]. Available: https://www.tindie.com/products/hcxqsgroup/4-nanovna-v2-plus4/

[9] Kjell & Company, "Raspberry pi 4 model b enkortsdator 8 gb ram," (Last visited 2023-12-15). [Online]. Available: https://www.kjell.com/se/produkter/dator/enkortsdator/raspberry-pi-4-model-b-enkortsdator-8-gb-ram-p88159?gad_source=1

[10] Kjell & Company, "Sandisk ultra micro-sd-kort 64 gb sdxc," (Last visited 2023-12-15). [Online]. Available: https://www.kjell.com/se/produkter/mobilt/minneskort/sandisk-ultra-micro-sd-kort-64-gb-sdxc-p65991

[11] PCBWay, "Pcbway pcb cost calculator," (Last visited 2023-12-15). [Online]. Available: https://www.pcbway.com/orderonline.aspx

[12] Kjell & Company, "Playknowlogy komponent-kit för experimentering med arduino," (Last visited 2023-12-15). [Online]. Available: https://www.kjell.com/se/produkter/el-verktyg/elektronik/utvecklingskit/arduino/arduino-kit/playknowlogy-komponent-kit-for-experimentering-med-arduino-p87293

[13] Biltema, "Kardborreband svart," (Last visited 2023-12-15). [Online]. Available: https://www.biltema.se/hem/kladvard/kladvardsrullar/kardborreband-svart-3-m-x-25-mm-2000053541