The RICE-BOX
A Proposal for the 2023 IEEE AP-S Student Design Contest

The RICE-BOX Group, Lund University

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1 Introduction

Seeing is believing, at least that is our conviction when it comes to physics. No educational method can spark the imagination of students in quite the same way as practical experiments with intuitive visualization methods. However, when new technologies emerge that build on decades of research and development, the working principles can seem too far away for students to grasp, even though they rely on the same fundamental principles that are taught in undergraduate courses. Intuition and deep understating of fundamental principles are massively important for up and coming engineers to be able to navigate through the noise of the technology industry. We believe that the best way for this understanding to develop is through interaction with the physical systems.

One emerging technology that can seem like magic but also holds great educational value through its reliance on fundamental physical principles is that of reconfigurable intelligent surfaces (RIS). Using the in-situ signal processing method RIS, intelligent radio environments can be created which some believe will represent "a new paradigm"[1] in signal processing.

We believe that this new paradigm can also be used to improve the teaching methods by which students learn about electromagnetic wave propagation and the underlying physics governing it. We therefore propose the Re-configurable Interactively Changing Education Box (RICE-BOX)* which will utilize RIS and augmented reality (AR) to improve students intuition about electromagnetic wave propagation.

How EM-waves interact with materials, other waves and the fact that phase differences play a large role in propagation is often not internalized by students, even after an undergraduate course in electromagnetic field theory. Having the possibility to demonstrate these effects in a practical experiment, utilizing the control of the environment achievable through RIS, and the visualization possibilities of AR, is a high value compliment to traditional teaching methods and experiments.

The RICE-BOX is designed to be easy to set up and use in a classroom setting by being designed to fit in a small box. Our hope is that the RICE-BOX will inspire users to think of their own applications for RIS and also to see the challenges which lies ahead for higher frequency communication systems. The RICE-BOX will primarily show one such use case of RIS; the redirection of a Wi-Fi signal around an obstacle for increased signal strength.

1.1 Background

RIS is often achieved through the use of metamaterials which control the reflection, refraction, and scattering of incident electromagnetic waves. Metamaterials are already used commercially in wireless communication[2] and radar[3] but are then located together with the transmission mechanism. RIS moves this metasurface to the previously uncontrolled environment between transmitter and receiver[4].

To achieve anomalous reflection of an incident plane wave off a surface, it should be created from a metamaterial introducing a controllable phase shift on the reflected wave. Consider the 2D case, where the surface lies on the x-axis and the incident wave travels in the xy-plane. If the incident angle to the surface normal is θ_i and the desired angle of reflection is θ_r, it was derived in [5] that a phase gradient of

$$\frac{\mathrm{d}\phi}{\mathrm{d}x} = \frac{2\pi n}{\lambda_0}\left(\sin\left(\theta_r\right) - \sin\left(\theta_i\right)\right) \tag{1}$$

must be introduced. Here, λ_0 is the free space wavelength of the wave and n is the refractive index of the

*RIS means RICE in Swedish. Hence, this is funny.

surrounding space. The main part of this project is thus to construct such a metasurface.

An obstacle in the form of a grounded sheet will partially shield the 2.4 GHz EM-waves and RICE-BOX will use this to block some of the signal between transmitter and receiver. This will allow us to better see the effect of the RIS.

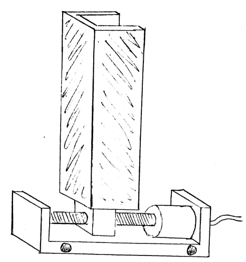

Figure 1: A sketch of one element.

2 Design and Setup

The RICE-BOX will consist of four primary parts: the reconfigurable surface, a transmitter, a receiver and an accompanying AR application. Here, these parts, the setup and properties to be measured will be detailed, followed by some preliminary simulation results.

2.1 Design of the Surface

We strive to create a surface where it is easy to understand the underlying physics of how the reflection angle is controlled. Therefore, a mechanical implementation seems suitable, where individual parts of the surface can be retracted to increase the path traveled before reflection. This results in different travel distances and thus a phase shift of the reflected wave which depends on where on the metasurface it was reflected. This is the basis of the beam forming ability of the surface. Essentially, this setup is therefore just an approximation of a slope, with the difference that the displacement of the elements are modulo $\lambda_0/2$.

It has already been shown in [6] that such an implementation is viable and this paper is the main inspiration for our design, however we will limit ours to the 2D case. This means that each element will be the full height of the surface, but only part of the width. The idea is to create a modular design with identical elements that can be manufactured independently and assembled to an arbitrarily wide surface using magnets as connectors. The element consists of a base plate with a stepper motor driven linear actuator on top. The facade, or the part that constitutes the actual surface, is mounted on the actuator. The facade is u-shaped and clad in copper tape. The base plate and facade will be 3D printed at Lund University. For control of the system, each element is connected to a central Arduino microcontroller. A sketch of an element is shown in figure 1.

The choice of dimensions are dependent on the choice of operating frequency. For this application, choosing the 2.4 GHz ISM band results in reasonable dimensions on the construction as well as a possibility for applications for Wi-Fi as intended, but also Bluetooth. The ESP32 board is chosen to receive and transmit Wi-Fi signals onto our RIS.

The elements are designed to be 6 cm wide. As the 2.4 GHz operating frequency has a free space wavelength of 12.5 cm, this yields a discretization of roughly two elements per free space wavelength. We propose to construct five such elements, and going for a square surface, this results in a total area of 30 cm $\times$ 30 cm, meaning roughly two and a half wavelengths in width and height.

2.2 Usage and AR Component

The transmitter and receiver will each comprise of an ESP32 board equipped with an antenna. The transmitting ESP32 will be placed far away from the metasurface to which the receiving one will connect, like a regular mobile device connecting to a Wi-Fi router. This allows the strength of the transmitter signal, reflected from the RIS, to be measured directly from the ESP32 itself [7] and sent to the AR app.

The AR app is envisioned to run on the students phone, the handheld device, which will identify the physical location of the transmitter, receiver and surface in a shared coordinate system. The technique is demonstrated in figure 2. Using the known location of the three parts from the AR app the required abnormal reflection of the surface can be calculated using equation 1. The measured signal strength of the receiver is sent continuously to the handheld device and shown in the AR app. This way, the app helps visualizing not the theoretical results, but the actual workings of the system. The app will be built using Apple's ARKit and will communicate with the

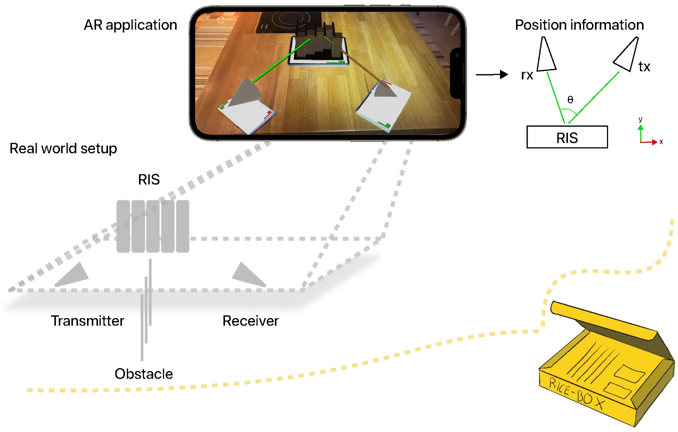

Figure 2: An overview of the contents of the RICE-BOX and a concept image of the AR app which shows the tracking of the transmitter, receiver and RIS.

RIS and receiver via http over Wi-Fi. Figure 2 also demonstrates a working AR app we wrote and shows that we can accurately track real world objects. Here the placement of the obstacle can also be seen.

2.3 Preliminary Simulations

Here we intend to prove that this design is capable of anomalous reflection using simulation software. The metasurface and its reflection pattern is simulated using the RF Module in COMSOL Multiphysics 6.1 (the software is used under an existing license at Lund University). †

The geometric setup simplifies the surface proposed above into five 6 cm wide, 30 cm tall blocks and can be seen in figure 3.

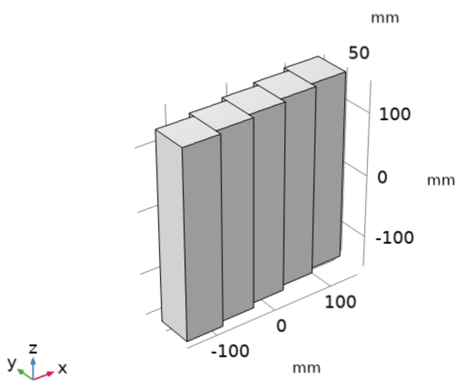

Figure 3: Geometry setup in COMSOL with relative element displacement $d = 10\,\mathrm{mm}$.

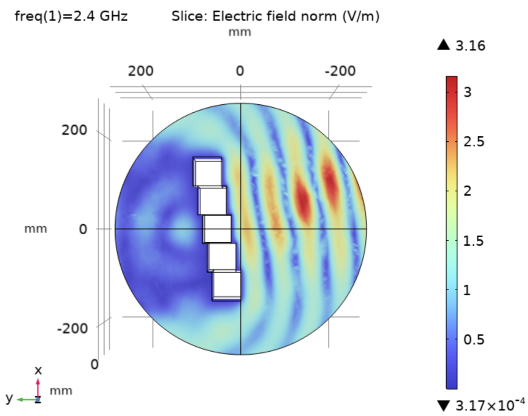

Figure 4: Simulated RIS reflection with $d = 10\,\mathrm{mm}$. Electric field norm in a $z = 0$ plane visualized using color. Note that the reflected field is larger than the incident $1\,\mathrm{V\,m^{-1}}$ in some areas.

The block property is set to *Perfect Electric Conductor* to simulate an idealized reflective surface, and the coordinates are set such that the elements move along the y-axis. Each block is successively moved a distance d, here referred to as relative element displacement, in the positive y-direction. A z-polarized plane wave is incident with an amplitude of $1\,\mathrm{V\,m^{-1}}$ and a frequency of 2.4 GHz is configured. The plane wave simulates an antenna placed far away from the surface, as intended in physical experiment. The scattered field is studied in two ways: figure 4 shows the scattered electric field norm near the RIS; figure 5 shows the far-field electric field norm in all directions for different values of relative element displacement d. ‡

† Specifically the settings are: Electromagnetics Waves, Frequency Domain (emw) physics; Frequency Domain study; Scattered Field formulation.

‡ The Far Field Calculation is only applied to directions pointing in the negative y direction, meaning in the front facing direction of the RIS.

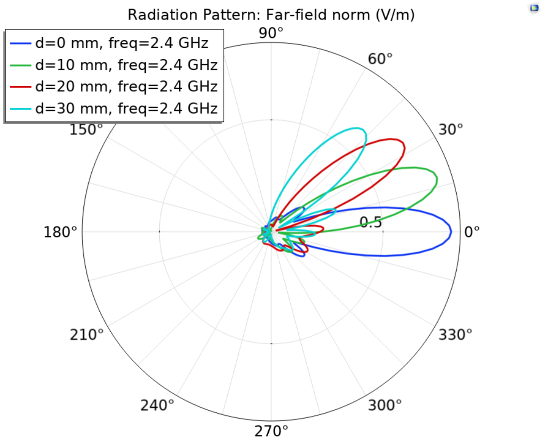

Figure 5: Simulated RIS reflection with $d = 0, 10, 20,$ and 30 mm. 0° is the negative y-direction.

From figure 5 the angle of the maxima with displacemnets $0, 10, 20, 30$ mm can be extracted as 0°, 18°, 34°, 48° respectively. Recalling equation 1 with $\theta_i = 0$, θ_r can be calculated if the phase gradient is known. Considering a wave propagating from $y = 0$, reflecting on a block surface at $y = md$, $m = 0, 1, 2, 3, 4, 5$ and back to $y = 0$, the reflected wave will have a phase shift of $\delta = 2\pi \cdot 2md/\lambda_0$.

Adjacent blocks being 6 cm apart along the x-axis gives a phase gradient of

$$\frac{\mathrm{d}\phi}{\mathrm{d}x} = \frac{\delta}{m \cdot 6\,\mathrm{cm}} = \frac{4\pi d}{\lambda_0 \cdot 6\,\mathrm{cm}}. \tag{2}$$

Inputting this to equation 1 with $n = 1$ gives

$$\theta_r = \sin^{-1}\left(\frac{2d}{6\text{ cm}}\right). \tag{3}$$

Thus the reflected angles are predicted to be 0°, 19.5°, 41.8° and 90° which only accurately predicts the lowest two values. It is clear that equation 1 is a simplification for this system, however it is worth emphasizing that somewhat predictable anomalous reflections are observed.

2.4 Properties to be Measured

Further studies in COMSOL could examine the reason for the discrepancy between predicted and simulated angles. We also see other questions to answer and parameters of the design to optimize, including: the response to different polarizations; using smaller element widths than 6 cm, i.e. a finer discretization; allowing the RIS to span a larger area than 30 cm × 30 cm; examining non-zero incidence angles and using non-conductive materials on the side parts of the elements. Another important feature to include is that for large d values, the displacement of some blocks will induce a phase shift larger than 2π. Thus, the modulo $\lambda_0/2$ function should be applied to the displacements to reduce the space taken up by the surface.

To construct the physical meta-surface, many different measurements outside of the simulations must also be made. We would for example have to measure the reflective properties of the copper tape to make sure it fulfills its purpose well enough. We would also have to calibrate the actuator rails and test the control software thoroughly to make sure the displacement of the elements is precise.

Once the design is optimized and the physical construction tests are done, there are several interesting properties to measure and analyze for the completed physical system. The reflecting properties of the RIS will be measured in an anechoic chamber at Lund University. The gain at various angles for different configurations will also be analyzed.

3 Bill of Materials

The bill of materials, based on a preliminary selection of parts, is presented in table 1. To the total cost, an extra 20% is added to cover anticipated extra costs. This makes the total \$310.

Table 1: The proposed bill of materials for the RICE-BOX. All prices in USD. Conversion rate used for sources in SEK: 1 SEK = 0.096 USD (December 28, 2022).

Item	Price	Source
Arduino Uno Rev. 3	\$28.8	Kjell & Company [8]
5x Linear actuator rail	\$52.3	AliExpress [9]
2x ESP32	\$63.2	Electrokit [10]
2x Cables	\$9.4	Electrokit [11]
3x Copper tape	\$28.8	Biltema [12]
3D printer filament	\$23.9	Clas Ohlson [13]
Antennas	\$30	Lund University
Magnets	\$20	Various
Total	**\$256.4**	
Total + 20% extra	**\$310**	

A The Team

The team consists of the following students and one mentor from Lund University:

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B Letter from Mentor

(Attached)

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