Feasibility and Quality of a MATLAB Implementation for an Intelligent Reflective Surface Final Report

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***Abstract*—This paper goes over the feasibility and overall quality of an Intelligent Reflective Surface (IRS) implementation in MATLAB. First, going over the general process and implementation, then giving multiple results demonstrating the level of control that the model has over the field distribution when determining the reflection coefficients over the IRS surface.**

***Index Terms*—Intelligent Reflective Surfaces, MATLAB, Electromagnetic Radiation**

I. Introduction

Intelligent Reflective Surfaces have been a hot topic for many researchers, and that is not for no reason. The ability to reflect a electromagnetic wave of a desired field distribution without a connected power source could have a massive impact on how we think about setting up environments that allow or disallow signals. This could range from getting better signal to your devices in your own home, to denying potential threats from intercepting sensitive information.

Due to the nature of IRSs being an array of N×N elements, many theoretical models may not be feasible (especially at a large scale) due to practical limitations. A major instances of such is when considering the use of varactor nodes for variable control of phase and magnitude. IRSs have been proposed that use multiple varactor diodes in-between each unit cell to continuously control the reflection phase of each unit [1]. If an IRS was 33×33 elements like the model used in this paper, and four varactor diodes were placed in-between each element, that would infer using more than 4,000 varactor diodes that only control reflection phase of the IRS. In addition "the response time of varactors is usually large, and the phase accuracy is far from satisfaction due to the analog control of varactors"[2]. Because of this, determining the level of phase and magnitude control needed to determine reflection coefficients should be tested.

II. Understanding the System

A. How the Intelligent Reflective Surface is Set Up

An IRS is a 2-Dimensional surface that has an array of N×N identical elements. The IRS modeled in this paper is 1×1 meter with 33×33 elements. 1×1 meter was chosen for convenience, although 33×33 elements is purposeful. Ideally elements in the x and y direction should be spaced at even intervals of $\lambda/2$. If we let our frequency be 5GHz, $\lambda/2 = .03$m. 1m/.03m gives us 33 elements. This configuration was used for all experiments seen in this paper.

B. How our Environment is Set Up

The Environment that this model will exist in has two objects. The IRS itself, and a 2-D observation surface where the field distribution will be observed five meters away from the IRS. In contrast to our IRS, the observation surface should be any size that is desired. To demonstrate this, the observation surface was set to be 2×4 meters. This set up was used for all experiments seen in this paper.

C. Assuming a Field Distribution over the IRS

In general Intelligent Reflective Surfaces are passive and have no power source connected, only made dynamic with the use of varactor diodes. In this paper the assumption is made that the incident wave being transmitted towards the IRS is uniform. This means you can consider the field distribution over the IRS instead of calculating the reflection coefficients.

$$\Gamma = E_r/E_i,$$

Assuming that E_r is the same all over IRS (uniform illumination) and is 1,

$$\Gamma = E_r.$$

Where E_r is the reflected wave over IRS, E_i is the incident wave over IRS, and Γ is the reflection coefficient.

III. Process of Finding the Field Distribution of a Reflected Wave

In order understand the model used in this paper, it is essential to know the process used to find the field distribution. Starting with a simple convolution of $r(x, y) * h(x, y) = s(x, y)$ where $r(x, y)$ is the input wave of the IRS system, $h(x, y)$ is the impulse response of the IRS and $s(x, y)$ is the field distribution found on the observation surface. In reality, the goal is to find the input wave $r(x, y)$.

The final field distribution should be known, for example if the goal was to bounce a wave through a hole in a wall, the hole has a known location in space. So, in fact, the goal is to find the input wave $r(x, y)$ that would create a field that only goes through the hole. In other words, the goal is to find an input wave $r(x, y)$ to replicate a desired field distribution $s(x, y)$. Once $r(x, y)$ is found, it should be put through the IRS system to see how accurate it replicates the desired field distribution. This accuracy or validity test will give the real field distribution produced by the IRS, which will be denoted as s'(x,y).

A. Isolating $r(x, y)$

Start with the convolution $r(x, y) * h(x, y) = s(x, y)$.

Applying a Fourier Transformation will result in a product of two waves:

$$R(k_x, k_y)H(k_x, k_y) = S(k_x, k_y)$$

Manipulate our function algebraically,

$$R(k_x, k_y) = S(k_x, k_y)/H(k_x, k_y)$$

Perform an Inverse Fourier Transform,

$$r(x, y) = F^{-1}[S(k_x, k_y)/H(k_x, k_y)]$$

IV. MATLAB Integration of Process

A. General Process

Now that the process is clear, it is time to create everything in MATLAB. starting with the creation of the δ function, which can be fed into the IRS to receive the impulse response. The δ function will be a matrix of 33×33 all zeros except for $\delta(17, 17) = 1$, a single value of 1 in the middle of the IRS.

The field distribution will have contributions from every element of the IRS. Iterations are done over every element of the IRS and adds its contributions to the field distribution of the observation surface. This can be done with the help of Greens Function: e^{-jkR}/R. The impulse field distribution can be seen in Fig.1.

Now, all that is needed is a field distribution to replicate $s(x, y)$, the process can then be used to receive the incoming wave $r(x, y)$.

B. Getting Phase in our $s(x, y)$ Prediction

The field distributions produced by the IRS are complex, and therefore have a phase and magnitude associated with them. Since this is the case, it is ideal that the prediction $s(x, y)$ should also be complex, but this is not something that can be easily done by manually associating phase to every xy-coordinate. To combat this, first the system is run normally and outputs a complex field distribution $s'(x, y)$ as expected. Then, only the phase is extracted from $s'(x, y)$ and is incorporated with the original prediction $s(x, y)$. This new distribution can be denoted as $s_{phase}(x, y)$. Finally, $s_{phase}(x, y)$ is treated as the distribution the system is trying to replicate and outputs a more accurate field distribution denoted $s'_{phase}(x, y)$.

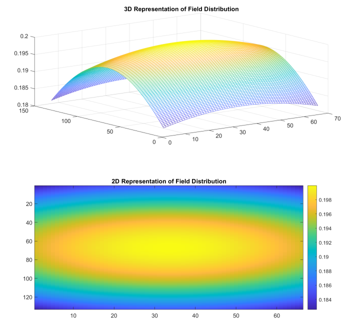

Fig. 1. Impulse Response $h(x, y)$ of the IRS.

Doing this solves a few notable problems that the previous iteration would experience, such as "middle cancelling" and inaccurately representing field distributions that covered a large area. "Middle cancelling" was a phenomena where the maxima of a field (spot) was directly in or close to the middle of the observation surface, the system would essentially ignore or "cancel" any other spots. As for the second case, large spots would have a substantial gradient from the edge to the middle of the spot, inaccurately representing the field.

C. Phase Iterating

As stated in the above section, the original distribution $s(x, y)$ has no phase associated, but eventually phase is added through a process. This process gives visibly better results in our distribution $s'_{phase}(x, y)$. From this point the same process can be done again, and take another iteration of updated phase values, which also produces marginally better results. This process can be repeated until sufficient, thus **phase iterating**. This iterative process can represented as $s_i(x, y)$ where i is the number of phase iterations went through.

V. Quality and Results of our Process

The field distribution $s(x, y)$ that was chosen to replicate in the paper can be seen by either of the leftmost figures in Fig.2. A large spot in the middle with smaller spots in all four corners. A total of six validity tests were done to test the accuracy of our model: $s(x, y)$, s_{phase}, s_2, s_5, s_{10}, s_{25}. The first being where **no** phase is associated, the second where phase **is** associated, the third where **two phase iterations** were performed, and so on. The Results can be seen in Fig.2.

As seen in the figures, greater phase iterations let the model perform better, but only to a certain extent. While the large square spot in the middle consistently gets more accurate (besides 10 phase iterations which may be due to destructive interference), the spots on all four corners seem to stay consistent after two phase iterations. This means there is a threshold in which more iterations result in negligible

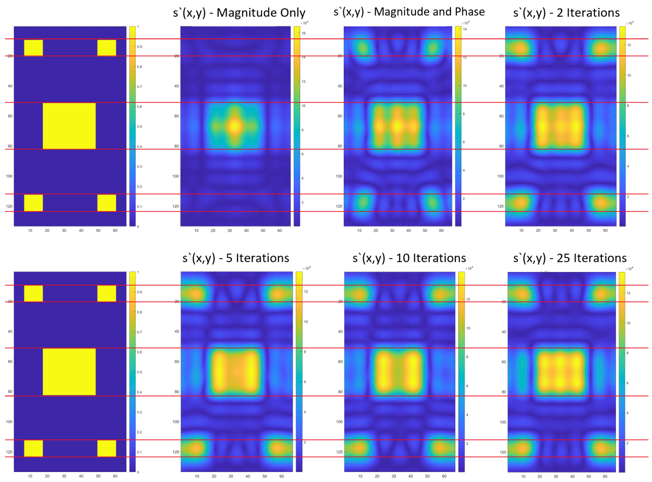

Fig. 2. Validity Tests from Process. Red Lines help determine margin of error.

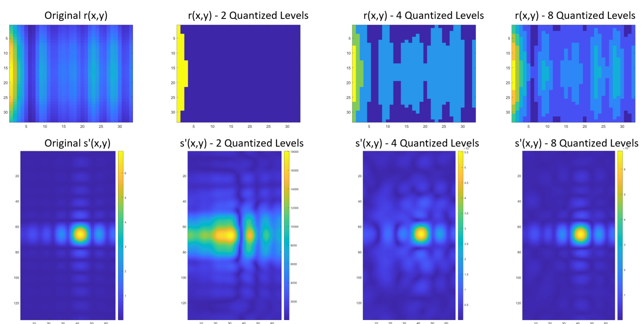

Fig. 3. Results of Quantizing Phase - Simple Field

improvements, and this threshold likely varies over every unique field distribution.

VI. Mag-Phase Quantization

In reality an IRS will not be able to replicate $r(x, y)$ exactly because the amount of values phase and magnitude can take on will be quantized depending on the digital to analog converter (DAC) and varactor diodes used. It would be beneficial to know how well this system can replicate field distributions when phase as well as magnitude is quantized. Taking this into account it was decided to test the accuracy when magnitude and phase was quantized into 2, 4, and 8 levels, seen in Fig.3.

As expected quantizing decreases the quality of the results, but usually still maintains a general sense of the distribution. At higher quantization levels there seems to be a high degree of accuracy. When trying to replicate more complex fields, the model behaves similarly, See Fig.4.

In addition to overall shape and distribution degrading with quantization, a sharp dip in magnitude can be observed on the color-bar to the right of each figure. This also naturally leads to the conclusion that there is a quantizing threshold. Depending on the use case of the IRS, this threshold could vary.

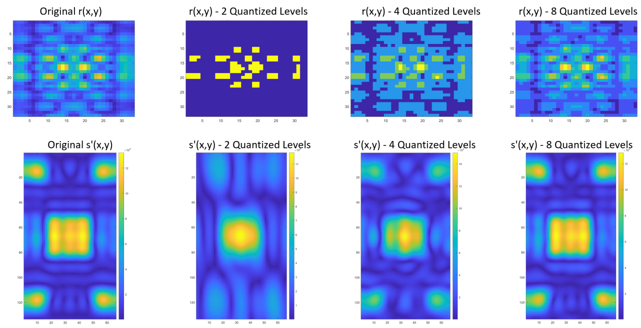

Fig. 4. Results of Quantizing Phase - Complex Field

VII. Conclusion

Seeing the accuracy that was achieved with this model I think it is clear to say that the use of this model to replicate behavior of an IRS is certainly feasible. The quality of the results seem quite promising so far, especially if a few shortcomings could be addressed. The red lines on Fig.2 demonstrate that the field distributions are largely contained within their respective boundary. While it still could be addressed further, the magnitude of the side lobbing is minimal. Quantizing the reflection coefficients could prove to be a problem, especially if someone could only allow a few quantization levels. Although promising results are shown if more were to be acceptable.

VIII. Future Work

Future work to improve the control and feasibility of using this model could be to address the dip in magnitude from mag-phase quantization.

Improving the quality of the resulting fields when using phase quantization could be addressed. A level of accepted accuracy may also prove useful.

Determining whether phase or magnitude has a greater effect on the final field distribution through quantizing one more than the other.

Experimenting with different sized IRS sizes and observation surfaces should be addressed, as the same setup was used for all the results seen here.

Ideally, these issues may be addressed and in the future a real world implementation of the surface could be produced

References

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