Intelligent Reflecting Surfaces Adaptive Beamsteering and PSK Direct Modulation

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***Abstract*—Intelligent Reflecting Surfaces (IRS), a planar array consisting of a large number of low-cost and low-complexity metal patch elements, is predicted to be among the key technologies in future wireless communications. This is mainly due to its capability to improve wireless energy and spectrum efficiency by reconfiguring the wireless environment in a smart and flexible way. IRS is capable of shifting the phase, amplitude, frequency, or even polarity of the impinging electromagnetic (EM) wave. However, only the phase-shift type of IRS is widely adopted in most scenarios. In this paper, we exploit the property of such IRS to directly modulate an incident EM wave with phase shift keying (PSK) modulation. We consider one transmit antenna that transmits a continuous single-tone electromagnetic (EM) wave, which is then modulated by the IRS and reflected toward the receiver. In addition to the theoretical explanation, we present simulation results with different modulation orders. Moreover, we validated the simulation results by experiment. Furthermore, we also proposed a beam scanning method to obtain IRS patterns to steer the beam towards the desired direction in an adaptive manner. One optimal pattern that maximizes the received power is then selected from the beam scanning codebook. By doing so, a wireless path strength can be significantly improved.**

***Index Terms*—intelligent reflecting surfaces, wireless communications, direct modulation, phase shift keying**

I. INTRODUCTION

Intelligent Reflecting Surfaces (IRS) is predicted to be one of the key technologies for the next generation of mobile communications. IRS is a planar array consisting of a large amount of dielectric patch (unit cell), each of which can be controlled individually to induce a manipulation of the impinging electromagnetic (EM) wave properties. By appropriately controlling the state of unit cells, one can do beamfocusing, multi-beam, or beam-scattering [1]. In contrast to phased-array antennas, IRS does not require active and power-hungry radio-frequency (RF) chains. Hence, the cost and complexity can be suppressed. Many works consider the IRS as a relay to improve the quality of wireless communication [2], to focus the beam [3], split the beam for multi-receiver [4], or provide an alternative wireless path in the non-line of sight (nLoS) scenario where the direct path is unavailable. In addition, some works exploit IRS potentials to improve the RF wireless power transfer (WPT) efficiency [5], [6] or to extend the range of the wireless coverage [7]–[9].

In many cases, the IRS is considered as a lens or reflector to relay the information from the transmitter to the receiver. Hence, the IRS has no capability to transmit its own information. In this paper, we propose an IRS-based direct modulation with a phase shift keying. The theory and simulation of the IRS adaptive beam steering toward the receiver, while implementing a direct modulation at the same time, is presented on this manuscript. The simulation is then validated by experiment on a 1-bit 5.8GHz IRS testbed with a 16×16 unit cells. This paper consists of five sections. In the first section, we present the introduction and the motivation. Then, an overview of the IRS, including theory, IRS spatial model, and IRS control model are briefly explained in the Section II. In Section III, we present the simulation and experiment results. Finally, the discussion and the conclusion are presented in the Section IV and V, respectively.

II. IRS OVERVIEW

A. *Programmable Metasurface Theory*

IRS has also been called a reconfigurable intelligent surface (RIS) or a programmable metasurface. At its early stage, traditional metasurface requires a specific design structure to achieve its objective of manipulating the incident wave (e.g., phase, magnitude, or frequency shift). Therefore, it is impossible to produce dynamic manipulation without changing the design structure of the metasurface itself. However, programmable metasurface or IRS shifts this paradigm. With the IRS, the manipulation can be configured dynamically such that an intelligent wireless propagation environment can be achieved. Although IRS can shift the phase, magnitude, or even frequency of the impinging wave, most of the recent IRS work only focuses on shifting the phase. Hence, in this paper, we consider the phase-shift type of IRS with n number of states. The resolution of the phase shift is obtained as 360° divided by the number of states n. In a scenario with the x- or y-polarized incoming EM wave, we can express the scattering field from the IRS with the size of $K \times L$ as [10]:

$$\begin{aligned} E(\theta,\varphi) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} & A_{kl} e^{j\alpha_{kl}} \cdot \Gamma_{kl} e^{j\phi_{kl}} \cdot f_{kl}(\theta,\varphi) \\ & \cdot e^{jk_0 (kd_x \sin\theta\cos\varphi + ld_y \sin\theta\cos\varphi)}, \end{aligned} \tag{1}$$

where A_{kl}, α_{kl}, respectively, indicate the relative illuminating amplitude and phase for each of the unit cell ($A_{kl} = 1$, $\alpha_{kl} = 0°$ if we consider plane wave source), Γ_{kl}, ϕ_{kl} are the reflection amplitude and phase of kl-th unit cell, $f_{kl}(\theta,\varphi)$ indicates the unit cell scattering pattern, and d_x and d_y are the unit-cell spacing in x- and y-axis. Theoretically, we can steer the impinging EM wave by utilizing the Equation (1). We exploit this property to form and steer the beam toward the receiver position. Then, we apply phase-shift keying (PSK) direct modulation on the IRS to modulate the single-tone incoming EM wave.

B. IRS Spatial Model

Let us consider the IRS-direct modulation system with one transmitter and one receiver. The transmitter antenna radiates a single tone unmodulated electromagnetic (EM) wave with wavelength λ. This wave is then reflected by the IRS and received by the receiver.

The IRS consists of $K \times L$ unit cells. The IRS, transmitter, and receiver are located along the y-z plane with their local coordinate systems (LCS). $(d^{\text{IRS,y}}, d^{\text{IRS,z}})$ indicate the spacing between unit cells in the IRS in the y and z direction, respectively. With a rectangular-shaped array of M and LCS, we define the position of the element (k, l) in the y-z plane as

$$\mathbf{u}_{k,l}^{M} = (d^{y}\kappa_{k}^{K}, d^{z}\kappa_{l}^{L})^{T}, \tag{2}$$

where $\kappa_{j}^{J} = j - J/2 - 1/2$, (d^{y}, d^{z}) indicate the element spacing in y and z directions. Therefore, we denote the position of unit cell (k, l) in the IRS as $\mathbf{u}_{k,l}^{\text{IRS}}$.

In this model, we assume that the transceiver lies in the far field region of the IRS. The distance between the origin of the IRS's LCS and the transceiver is denoted by $r^{\text{Tx-IRS}}$ and $r^{\text{IRS-Rx}}$. Each of which is for the transmitter distance and receiver distance. We define the direction from the transmitter to the IRS as $(\theta^{\text{IRS-Tx}}, \phi^{\text{IRS-Tx}})$ from the IRS point of view. Similarly, the direction from the receiver to the IRS is presented by $(\theta^{\text{IRS-Rx}}, \phi^{\text{IRS-Rx}})$. These direction angles can be presented in the u-v coordinate format. For example, the u-v coordinate of the direction from the IRS to the transmitter is presented as

$$\mathbf{s}^{\text{IRS-Tx}} = (\sin\theta^{\text{IRS-Tx}}\cos\phi^{\text{IRS-Tx}}, \sin\theta^{\text{IRS-Tx}}\sin\phi^{\text{IRS-Tx}})^{T}. \tag{3}$$

Similarly, the u-v coordinate for $\mathbf{s}^{\text{IRS-Tx}}$, $\mathbf{s}^{\text{IRS-Rx}}$, and $\mathbf{s}^{\text{Rx-IRS}}$ can be obtained in the identical manner.

C. IRS Control Model

A typical IRS consists of hundreds to thousands of controllable unit cells (i.e., by using PIN diode, varactor, liquid crystal, etc.). The IRS can convert the incident free-space EM wave into a guided wave, which is then re-radiated to the air. In this subsection, we present high-level IRS direction control parameters. We obtain the reflection coefficient of the unit cell as

$$\Gamma = \frac{z-1}{z+1} = |\Gamma| \exp j\varphi, \tag{4}$$

where z and φ respectively, is the normalized impedance of the unit cell and the reflection phase.

Under the far-field region assumption, we obtain the direction control parameter to steer the incident wave from the IRS to $(\theta^{\text{IRS}}, \phi^{\text{IRS}})$ as

$$\mathbf{c} = (\sin\theta^{\text{IRS}}\cos\phi^{\text{IRS}}, \sin\theta^{\text{IRS}}\sin\phi^{\text{IRS}}). \tag{5}$$

Then, by adjusting the phase control parameter ω, we can control the phase of the reflected wave from the IRS. Therefore, the reflection coefficient of the unit cell (k, l) is set as

$$\Gamma_{k,l}(\mathbf{c}, \omega) = \exp\big(j\omega\big)\exp\Big(-j\frac{2\pi}{\lambda}\mathbf{c}^{T}\mathbf{u}_{k,l}^{\text{IRS}}\Big). \tag{6}$$

Let us assume that the unit cell is carefully designed so that the reflection coefficient $\Gamma_{k,l}$ is constant. By controlling the reflection coefficient, we are able to shift the phase of the reflected wave, that is,

$$\Gamma_{k,l} = \exp(j\zeta_{k,l}), \tag{7}$$

where $\zeta_{k,l}$ is the phase shift induced by the IRS. Depending on the type of controllable load, the phase shift can be continuous or discrete. However, a typical IRS usually provides only discrete phase shifts. For example, in one-bit IRS, the phase shift can be 0 or π. While, in two-bit IRS, the phase shift can be 0, $\pi/2$, π, or $3\pi/2$. In this work, we assume that there are at least two available phase shifts (i.e., 0 and π).

Further, the received wave at the receiver is obtained as

$$y = \left(\sum_{k=1}^{K^{\text{IRS}}}\sum_{l=1}^{L^{\text{IRS}}} h_{(k,l)}^{\text{Tx-IRS-Rx}} + h^{\text{Tx-Rx}}\right) \times x, \tag{8}$$

where x denotes the radiated wave from the transmit antenna, $h_{(k,l)}^{\text{Tx-IRS-Rx}}$ denotes the channel gain from the transmitter to the receiver through unit cell (k, l) of IRS, and $h^{\text{Tx-Rx}}$ is the direct channel gain from the transmitter to the receiver.

The maximum gain of the beam from the IRS is directed to the receiver when the direction control of the IRS is set as $\mathbf{c} = \mathbf{s}^{\text{IRS-Tx}} + \mathbf{s}^{\text{IRS-Rx}}$. Hence, to maximize the received power on the receiver side, we should find the appropriate direction control $\mathbf{c}$ of the IRS. In this work, we iteratively scan the IRS using the predefined code beams. Then, the receiver periodically sends the power information to the transmitter. By utilizing the power information which corresponds to each of the beams within the codebook, the IRS controller on the transmitter side finds the most appropriate $\mathbf{c}$, which results in the maximum received power. Finally, we iteratively adjust the phase control parameter w of the IRS to align the phase of the received signal.

III. RESULT

A. Simulation Result of 1-bit IRS-based BPSK Modulation

By using the fact that we are able to optimize the IRS pattern to steer the beam to the desired point and the fact that the considered IRS at least provides us 0° or 180° phase shift, theoretically we can achieve the BPSK modulation without deteriorating the received power, simply just by inverting the optimal pattern (See: Fig. 1). By doing so, we are able to steer the beam to the identical point with a similar amplitude but with a 180° phase shift. In Table I, we can see the result obtained from Matlab simulation for 16×16 unit cells IRS with a plane wave source.

By assuming a perfect transmission and ignoring path loss and interference, we managed to achieve a perfect BPSK modulation with identical amplitude and 180° phase shift as presented in Fig. 2. Further, as we can see in Fig. 3, there is no difference in steering angle and amplitude when we vary the IRS with 0° and 180° phase shift.

Therefore, by directly modulating the transmitted sine wave using IRS, we can send information through the wireless channel. To demonstrate the system, in this paper, a ball image is modulated through an IRS using BPSK modulation.

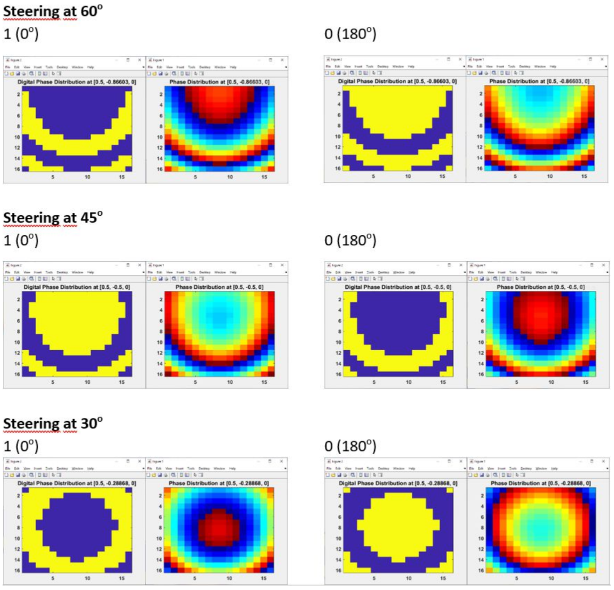


Fig. 1. Digital Phase Quantization and Its Corresponding Continuous Phase Distribution for BPSK Modulation while Steering at $30°, 45°$, and $60°$.

TABLE I
MATLAB SIMULATION RESULT FOR BPSK MODULATION

Modulation	Received Magnitude (dB)	Received Phase (°)
	30°, 50 cm	
1 (0°)	130.8711	-122.7485
0 (180°)	130.8711	67.2515
	45°, 50 cm	
1 (0°)	150.5554	72.1426
0 (180°)	150.5554	-107.8574
	60°, 50 cm	
1 (0°)	43.2276	-90.066
0 (180°)	43.2276	89.934

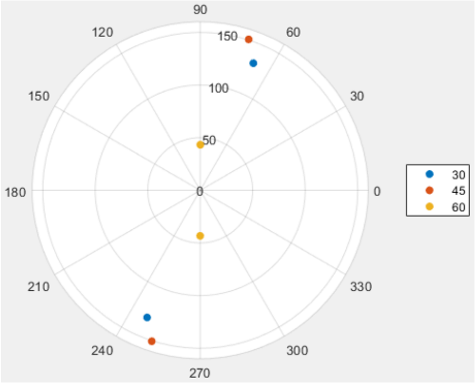
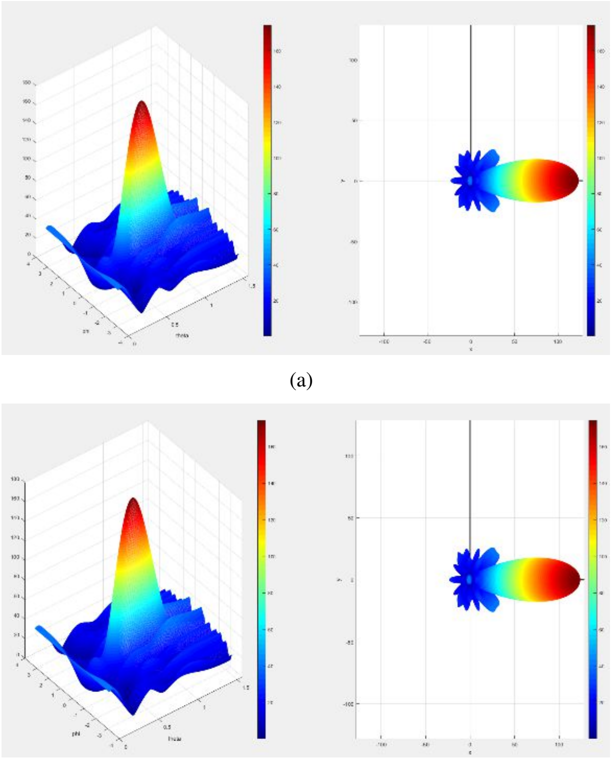


Fig. 2. BPSK Modulation Result for the Beam Steered at $30°, 45°$, and $60°$.

Since the BPSK modulation provides only two modulations (i.e., 0° and 180° phase shift), for simplicity, we modulated only a black and white image (See: Fig. 4). Thus, we first convert the image into grayscale. Then, we convert the grayscale image into black and white. After that, the image resolution is resized to 28×28 pixels. Note that our decision to convert the image into black and white and resize it into 28×28 pixels is just for simplicity purposes. Hence, the actual data is not limited to these parameters.

In Fig. 5(a), we can see the ball image after it was converted into black and white and resized into 28×28 pixels, along with its corresponding signal modulation. The IRS modulates the incident EM wave according to this modulation and re-radiates toward the receiver. Then, in Fig. 5(b), we can see the signal received by the receiver and the image after the demodulation process. Since we ignored the path loss and interference in this simulation, the data was transmitted and received perfectly. However, in the measurement case, which is explained in the next part, we can see some imperfections occur.



(a)

(b)

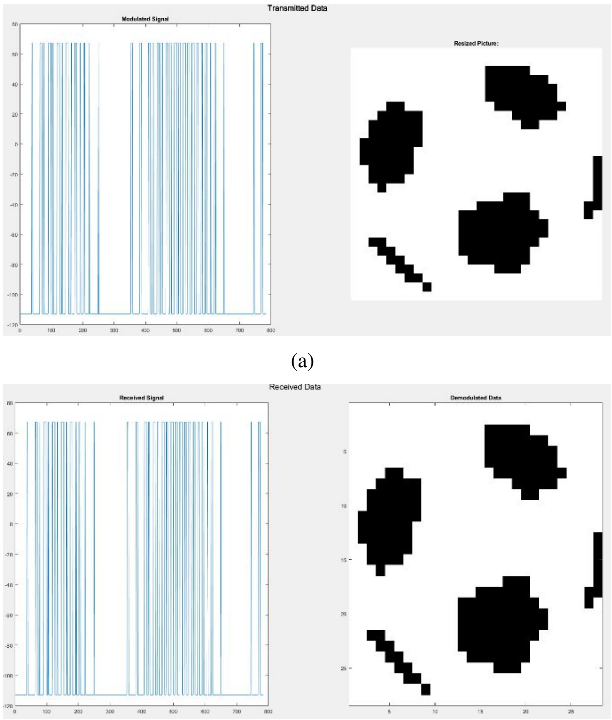
Fig. 3. Simulation Result of 3D Beamshape Plot for the Beam Steered at 45°. (a) Modulation 1 (0°) and (b) Modulation 0 (180°).

(a) (b) (c)

Fig. 4. Sample Ball Image. (a) Original. (b) Grayscale. (c). Black and White.

B. Experiment Result of 1-bit IRS-based BPSK Modulation

To validate the theory and simulation result, we conducted a measurement with a real 5.8GHz 1-bit IRS testbed. First, we validate the beam steering capability towards various angles (See: Fig. 1). It is observed that the beam can be adaptively steered toward the desired position. Then, we validate the pattern-flipping method for the direct modulation. As presented in the simulation result, we expect to see no difference in steering angle and amplitude when we modulate the signal with 0° and 180° phase change. However, as depicted in Fig. 7, the measured beam shape of the 0° and 180° modulation is slightly different. This is due to the imperfection of the environment setup, hardware fabrication error, and natural measurement noise. Nevertheless, since the



(a)

(b)

Fig. 5. (a) Image to Send with its Corresponding Modulated Signal. (b) Received Signal and the Image After Demodulation.

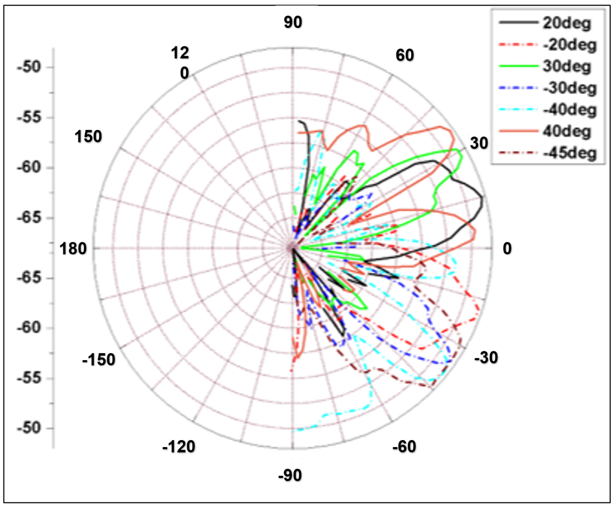
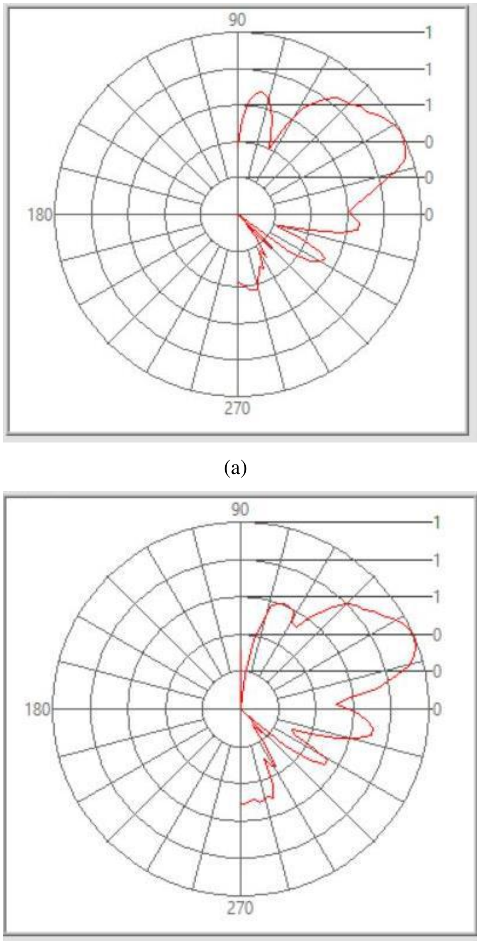


Fig. 6. Experiment Result of Beam Steering towards Various Angles.

angle and the magnitude difference of the main lobe of the beam are relatively small, we consider this result acceptable.

By using a similar approach, a black and white ball image is transferred through the experimental testbed. First, the ball image is converted to black and white, and then its resolution is resized to 28×28 pixels before being transmitted through the IRS direct modulation.

Fig. 8 presents the S21 and phase that are received by the receiving antenna through the experiment. We expect to see a similar S21 magnitude value and 180° phase difference between the modulations. However, as we can see in Fig. 8, although the magnitude value are relatively similar and average phase difference is around 180°, there are some imperfections. However, after the decoding process, the data can still be decoded correctly with no bit error, as in Fig. 9.



(a)

(b)

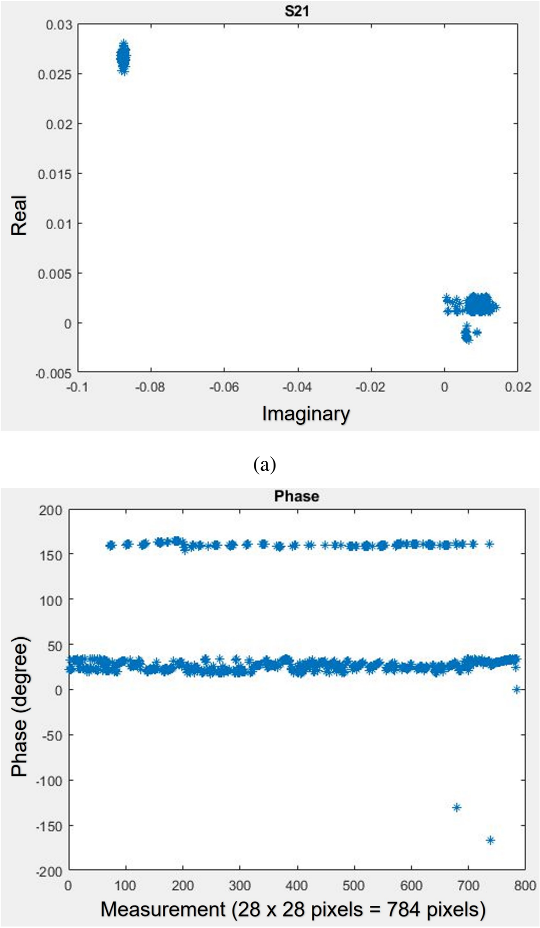
Fig. 7. Experiment Result of Beamshape Plot for the Beam Steered at 45°. (a) Modulation 1 (0°) and (b) Modulation 0 (180°).

TABLE II
MATLAB SIMULATION RESULT FOR QPSK MODULATION

Modulation	Received Magnitude (dB)	Received Phase (°)
	45°, 50 cm	
3 (0°)	187.8307	71.4537
2 (90°)	187.8307	161.4537
1 (180°)	187.8307	251.4537
0 (270°)	187.8307	341.4537

C. Simulation Result of IRS-based QPSK & 8PSK Simulation

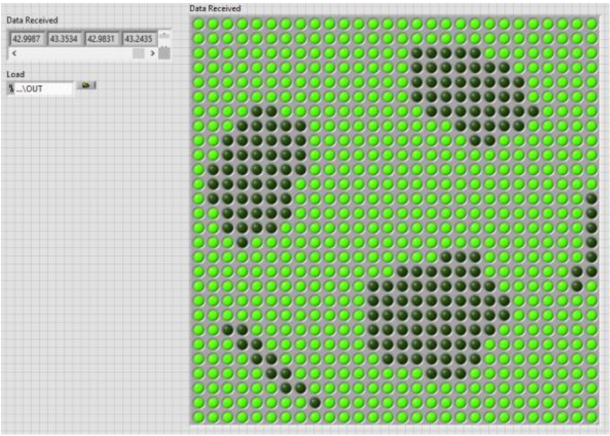
In this part, we present the possibility of extending the modulation order to the QPSK and 8PSK modulation. Thus, a higher bitrate can be achieved. We can achieve the modulation with a similar step as BPSK that is explained before but using an IRS with a larger number of bits. Instead of employing a 1-bit IRS, which can only provide a phase shift of either 0° and 180°, by increasing the number of the IRS bit into 2-bit or 3-bit, we will have a higher number of available states. For example, by having a 2-bit IRS, we can have either 0°, 90°, 180°, or 270° phase change, while 3-bit IRS will provide eight different states. Another advantage of having a larger number of bits is that we can achieve a higher magnitude due to a smaller phase shift resolution. In Fig. 10, we present the simulation result of the QPSK and 8PSK modulation.



(a)

(b)

Fig. 8. (a) S21 Magnitude and (b) Phase Received by the Receiver Antenna, Measured using Anritsu Virtual Network Analyzer.



Data Received

42.9987 43.3534 42.9831 43.2435

Load

...\OUT

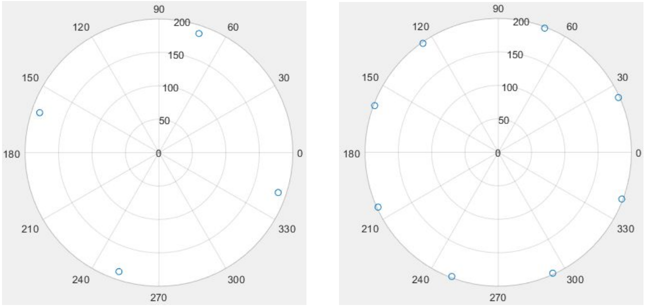
Fig. 9. Demodulated Signal Shows No Bit Error.

IV. DISCUSSION

As we can see in Table II and Table III, we can achieve a larger magnitude by increasing the number of bits. This is due to the better phase control resolution of the higher bits. A larger number of bits also provides a higher modulation order and hence, a higher transmission rate. However, it is very challenging to provide a PIN diodes-controlled IRS structure which can provide more than 2 bits due to the cost and complexity. In addition, a higher modulation order tends to be more fragile from the attenuation and noise due to the naturally higher BER. In this work, the modulation rate is limited by the switching speed of the IRS components (i.e., PIN diodes and shift register ICs). Several researchers have used a different approach to control the IRS. Research [11], [12] proposes a continuous phase control IRS by using a varactor instead of PIN diodes. While the mushroom structure in [11] caused the deficiency in the phase tuning range, [12] resolved this deficiency using a different approach. Further, [13] came up with liquid crystals to control the state of the IRS.

TABLE III
MATLAB SIMULATION RESULT FOR 8PSK MODULATION

Modulation	**Received Magnitude (dB)**	**Received Phase (°)**
	45°, 50 cm	
7 (0°)	198.1425	159.3976
6 (45°)	198.1425	204.3976
5 (90°)	198.1425	249.3976
4 (135°)	198.1425	294.3976
3 (180°)	198.1425	339.3976
2 (225°)	198.1425	24.3976
1 (270°)	198.1425	69.3976
0 (315°)	198.1425	124.3976



(a)

(b)

Fig. 10. Simulation Result of Polar Plot for the Beam Steered at 45°. (a) QPSK Modulation and (b) 8PSK Modulation.

We can theoretically achieve a narrower beam shape by increasing the number of unit cells based on the simulation and measurement results. Hence, the received power can be increased. However, increasing the number of unit cells might expense in a higher cost and complexity. Moreover, in a low-frequency IRS, a massive number of unit cells makes the IRS bulky. However, in the higher frequency (mmWave or even sub THz), a larger number of unit cells might be feasible due to the smaller size of unit cells. Other methods, such as Frequency Shift Keying [14] and harmonic amplitudes & phases via a time-domain [15], have been implemented using IRS. Study [16] used a coding sequence to conduct a direct modulation via programmable coding IRS. By doing so, the message security is guaranteed since the user needs to decode and merge the data received by all receivers to get the full message. Lastly, with the help of machine learning to estimate the wireless channel and obtain the appropriate IRS pattern, an IRS-based multi-user communication can be achieved.

V. CONCLUSION

In this work, we propose a PSK direct modulation method for an IRS-based communication system with an adaptive beam steering algorithm. We exploit the property of the phase-shift type IRS to directly modulate an incident EM wave with phase shift keying (PSK) modulation. We consider one transmit antenna that transmits a continuous unmodulated electromagnetic (EM) wave, which is then modulated by the IRS and reflected toward the receiver. Through simulations and experiments, we have validated the proposed system.

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