The Smart Mirror: Reconfigurable Intelligent Surfaces for ISM Applications

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ABSTRACT:

This study focuses on the design and implementation of a Reconfigurable Intelligent Surface (RIS) for ISM band applications at 5.8 GHz to improve wireless communication in industrial settings. An RIS is a smart, passive surface that can control and reflect wireless signals in a desired direction by adjusting the phase of the reflected waves. The proposed system uses a 6×6 RIS patch array controlled by PIN diodes, which allows the signal to be dynamically steered toward the receiver. The research methodology was initiated with analytical modeling in MATLAB to establish the theoretical framework and perform initial phase calculations. Subsequently, the design was implemented in the CST Studio Suite for detailed electromagnetic simulations and verification. The primary focus of this investigation was the analysis of the reflection phase difference provided by the unit cells. Using this dual-platform approach, numerous simulation iterations were conducted to characterize the behavior of the array under various states.

From the extensive data generated in both MATLAB and CST, specific outputs were selected based on their relevance to the desired beam steering characteristics. The analysis of these selected results demonstrates the practical feasibility of the RIS design for manipulating the signal reflection phases. The study confirms that the proposed configuration can effectively support signal enhancement objectives, making it a viable solution for improving reliability in Industrial IoT and smart manufacturing environments.

The implementation demonstrated improved signal strength, enhanced coverage, reduced latency, and energy-efficient communication. The proposed RIS-assisted system provides a reliable and cost-effective solution for industrial IoT applications, making it suitable for smart manufacturing, machine-to-machine communication, and future industrial automation.

I. INTRODUCTION

Industry 4.0 has greatly changed modern manufacturing by using Internet of Things (IoT) devices to monitor machines, predict failures and automate industrial processes. These systems rely heavily on wireless communication s. However, in industrial environments, wireless signals often face problems owing to metal structures, large machines, and strong radio-frequency interference. These factors cause weak signals, coverage gaps, and unreliable connections in the communication system.

Reconfigurable Intelligent Surfaces (RIS) offer a new and advanced solution to these communication challenges. An RIS is a special surface made of programmable materials that can control the propagation of wireless signals. By adjusting the phase of the electromagnetic waves through software, the RIS can redirect and strengthen the signals. Unlike traditional wireless systems that only adapt to the environment, the RIS actively modifies the environment to improve communication performance.

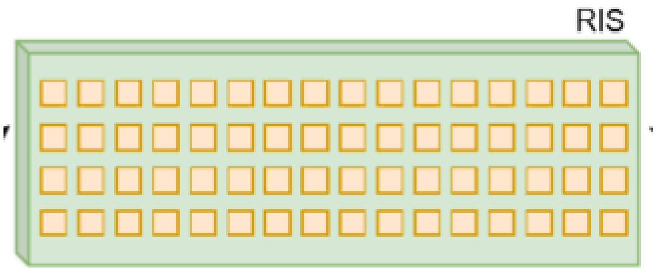


Figure 1. RIS panle.

The 5.8 GHz frequency band is well suited for industrial applications because it supports higher data rates and experiences less interference from common consumer devices. It also provides better performance in industrial settings than lower frequency bands. The E-byte E103-RTL8811CU dual-band Wi-Fi module, which uses the Realtek RTL8811CU chipset, supports both 2.4 and 5.8 GHz bands, making it a suitable choice for implementing RIS-based Industrial IoT systems.

This study focuses on demonstrating how RIS technology can improve the reliability and coverage of Industrial IoT communication at 5.8 GHz. By addressing wireless connectivity issues in smart manufacturing environments, the proposed system aims to ensure stable and efficient communication between sensors, actuators, and control systems.

II. LITERATURE REVIEW

Recent studies [1] by Zhang et al. (2020) explained the basic working principles of Reconfigurable Intelligent Surfaces (RIS). Their research showed that programmable metasurfaces can control and modify electromagnetic waves to improve wireless signal strength and coverage. The study reported that an RIS can improve the received signal strength by 10–15 dB while reducing power consumption by 50–70% compared with traditional active relay systems. This makes RIS an energy-efficient and effective solution for enhancing wireless communication.

[2] Liu and Chen (2021) discussed the major challenges faced by wireless communication systems in industrial environments. These challenges include signal blockage caused by large metallic machines and structures, electromagnetic interference generated by industrial equipment, and coverage dead zones owing to complex factory layouts. Additionally, industrial applications require highly reliable communication, especially in mission-critical operations, where delays or failures can cause serious issues.

Research conducted by [3] Kumar et al. (2022) highlighted the benefits of using the 5.8 GHz frequency band for industrial applications. The study showed that 5.8 GHz supports higher data rates of up to 433 Mbps and experiences less congestion than the commonly used 2.4 GHz band. It also offers better compatibility with existing industrial systems, making it suitable for real-time monitoring and control.

Recent work by [4] Thompson and Rodriguez (2023) explored the use of RIS in smart factory environments. Their findings demonstrated a 300% improvement in network throughput, improved wireless connectivity for

Autonomous Guided Vehicles (AGVs), and enhanced reliability of predictive maintenance systems. The study also emphasized that RIS can extend wireless coverage in a cost-effective manner without the need for additional base stations.

[5] Park et al. (2022) studied the integration of systems based on the RTL8811CU Wi-Fi chipset. Their research showed successful implementation with embedded platforms, such as Raspberry Pi, for IoT applications. The module offers easy plug-and-play connectivity through standard USB interfaces, making it convenient for industrial and embedded system deployment.

III. PROBLEM DEFINITION

Industrial Internet of Things (IIoT) systems rely heavily on wireless communication to enable real-time monitoring, automation, and machine-to-machine interactions. However, achieving reliable, low-latency wireless communication in industrial environments remains a significant challenge. Factory floors are typically filled with metallic machinery, dense structural layouts, moving equipment, and electromagnetic interference sources. These conditions severely affect signal propagation and degrade the overall network performance.

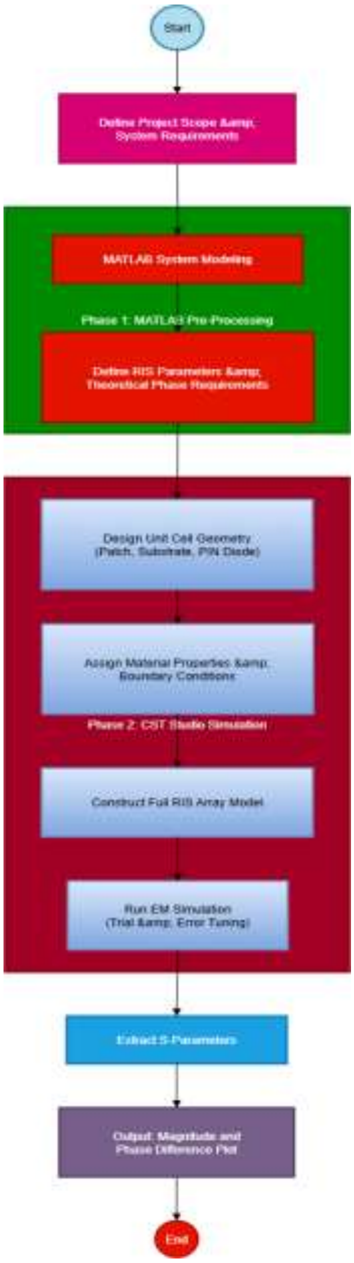
Conventional wireless communication systems cannot effectively handle these challenges because they can only adapt to transmission parameters such as power, modulation, and coding schemes. They lack the ability to control or modify the wireless propagation environment. Consequently, industrial wireless networks often experience coverage dead zones, high packet loss, unstable connections, and increased latency, which are unacceptable for mission-critical industrial applications that require high reliability and real-time performance.

Industries frequently deploy additional access points, repeaters, or wired infrastructure to compensate for poor connectivity. This approach significantly increases the deployment cost, power consumption, and maintenance complexity, while still failing to provide flexible adaptation to dynamic industrial environments, where machinery and layouts change frequently.

Furthermore, the use of higher-frequency bands, such as 5.8 GHz, although beneficial for higher data rates and reduced congestion, suffers from increased path loss and sensitivity to obstacles. Without intelligent signal control, these limitations restrict the effective use of frequency bands in industrial IoT applications.

Therefore, a cost-effective, energy-efficient, and adaptive wireless communication solution that can intelligently manage signal propagation, eliminate coverage dead zones, improve reliability, and meet the strict latency and performance requirements of industrial IoT systems is required. This study addresses the design and implementation of a practical Reconfigurable Intelligent Surface (RIS)-assisted wireless communication system capable of enhancing industrial IoT connectivity in the 5.8 GHz ISM band.

IV. METHODOLOGY



V. FUNDAMENTALS AND OPERATIONAL PRINCIPLES OF RIS

This section introduces the core principles of RIS operation, its interaction with EM signals, and an overview of standard RIS functions along with their fundamental principles and characteristics, which influence the performance of both individual elements and RIS arrays as a whole.

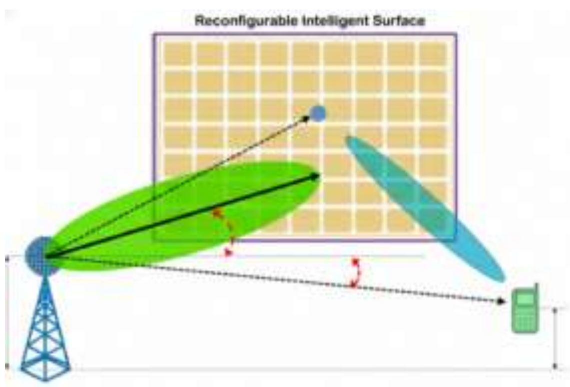


Figure 2. Electromagnetic-based elementary functions.

A. ANALYSIS OF THE RANGE AND OPERATING PRINCIPLES OF RIS

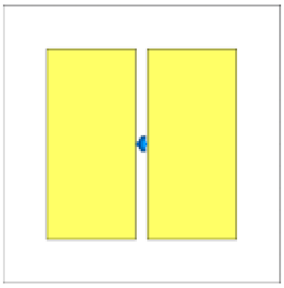
Fig. 2 illustrates the versatile capabilities of RIS in dynamically controlling electromagnetic wave propagation through a set of electromagnetic-based elementary functions, which enable the RIS to perform a wide range of operations in modern wireless communication systems. These functions include reflection, where the RIS steers the incident signals toward the desired direction, and refraction, which bends waves as they pass through the surface. An RIS can also achieve absorption to suppress or dissipate unwanted signals, whereas focusing enables the concentration of energy onto specific target points to enhance the signal strength. Through collimation, the RIS aligns the divergent beams into parallel beams for more efficient propagation. The polarization function allows the RIS to modify the polarization state of the electromagnetic waves to match the receiving antenna or mitigate interference. Additionally, RIS can perform splitting by dividing incoming signals into multiple beams directed at different users and supports analog processing directly on the surface, such as filtering or waveform shaping. Collectively, these elementary functions based on electromagnetics underscore the programmability and adaptability of RIS, positioning them as a fundamental technology in future intelligent wireless environments.

B. SIMULTANEOUS TRANSMITTING AND REFLECTING RIS

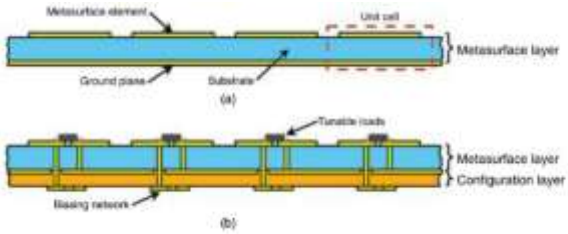
Traditional wireless systems suffer from "dead zones" where signals cannot reach the receiver. This project addresses this by using a 6 × 6 metasurface consisting of 36-unit cells. Each unit cell features a metallic patch with dimensions of lambda/6 (approximately 8.6 mm). This sub-wavelength sizing is critical because it allows for a finer spatial resolution when manipulating the phase of the incident wave, thereby enabling more precise beam steering.

To achieve "reconfigurability," each of the 36 patches was integrated with an SMP1345-079LF PIN diode. In the context of our work, these diodes act as the switching hearts of the metasurface. When the diode is in the ON state, it presents a low resistance, changing the surface impedance of the patch; in the OFF state, it acts as a capacitor. By toggling these states, a 1-bit phase shift (usually 00 and 1800) can be achieved. This allows the 6 × 6 array to "program" the electromagnetic environment, performing functions such as anomalous reflection to steer signals around obstacles.

C. UNIT CELL DESIGN



a. Patch



b. Layer Design

Figure 3. Unit Cell

The unit cell was designed in a square shape (Fig. 3 a). As shown in Fig. 3a, the unit cell consists of three layers. The unit cell parameter values (see Table 1) were obtained from simulations and optimizations using CST Studio software. The proposed RIS is designed to operate at 5.8 GHz and is fabricated on an FR-4 substrate with a loss tangent (tan δ) of 0.0031 and permittivity (εr) of 3.6. Although some studies have shown that RIS is useful for mitigating path loss in the mm-Wave frequency band, we decided to conduct the experiment at 5.8 GHz. We selected 5.8 GHz as the target operating frequency since 5.8 GHz frequency is part of the free and pervasive industrial, scientific, and medical (ISM) band. In addition, 5.8 GHz was chosen as the operating frequency to minimize the challenges of the experimental setup that might occur in the mmWave band. These challenges include the high cost of mmWave transceivers and RIS design complexity. Moreover, one of the main contributions of this study is to validate the theory and hypothesis that the RIS improves wireless communication quality through experiments rather than implementing the model itself in the mmWave frequency band.

Specification	Values
Operation Frequency (GHz)	5.8
Dimensions W*L*T (mm^3)	8.6 x 8.6 x 1.635
RIS substrate	FR-4 (lossy)
PIN de	SMP1345-079LF

Table 1:

To control the phase of the incident wave, a PIN diode was connected to each unit cell. As shown in Fig. 6, in the ON state, the PIN diode is equivalent to a series circuit of resistance and inductance, whereas in the OFF state, it is equivalent to a series circuit of capacitance and inductance. Therefore, under the EM wave illumination, the PIN diode impedance can be modeled as

$$z_L = \begin{cases} R + j\omega L\,, & ON\ state \\ j\omega L + \dfrac{1}{j\omega C}, & OFF\ state \end{cases}$$

The reflection coefficient can be obtained from

$$\Gamma = \frac{Z_L - Z_R}{Z_L + Z_R} = |\Gamma| e^{j\alpha}$$

where Z_R denotes the radiation impedance of the unit cell. The unit cell structure was designed to provide an appropriate value of Z_R to obtain a 180◦ phase shift between the ON and OFF states at the operating frequency. With the proposed design, a 180◦ phase shift between the ON and OFF states at 5.8 GHz can be achieved (see Fig. 7). This result is consistent with the measurement results of the fabricated unit cell. In the simulation result, a 180◦ phase difference between the ON and OFF states at 5.8 GHz was achieved, whereas in the measurement result, the frequency with the correct phase shift value was slightly lower. The imperfection of the measurement setup caused this slight difference, which is acceptable.

D. SIMULATION RESULTS

i. MATLAB outputs:

To simulate the proposed model, first, we have made the RIS simulator environment using MATLAB software. We then conducted simulation tests and analyzed the results. Fig. 4 shows the coordinate systems of the RIS and antennas. In the model, a spherical coordinate system was used for the simulations and experiments. The transmitting and receiving antenna locations are denoted by (r, θ, φ) with respect to the RIS positions. The RIS was located at (0 m, 0◦, 0◦). In the simulation, the whole-array MP training algorithm was implemented on an RIS with 6 × 6-unit cells.

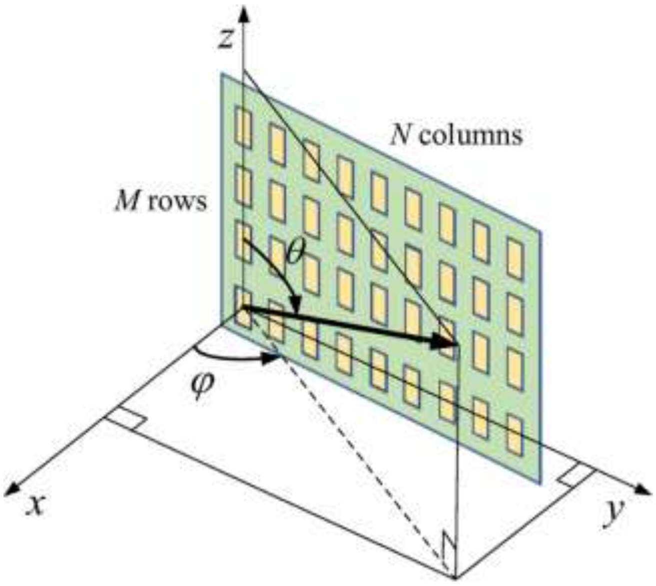
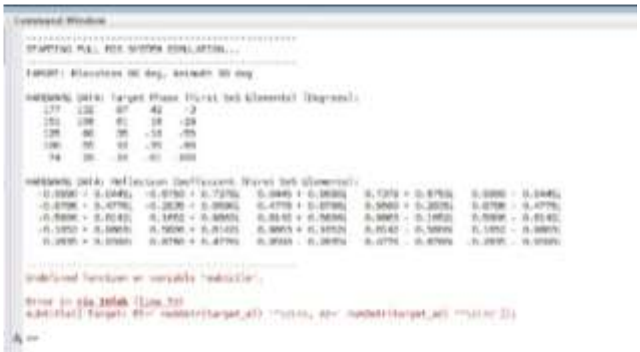


Figure 4: RIS model in the Cartesian and spherical coordinate systems.



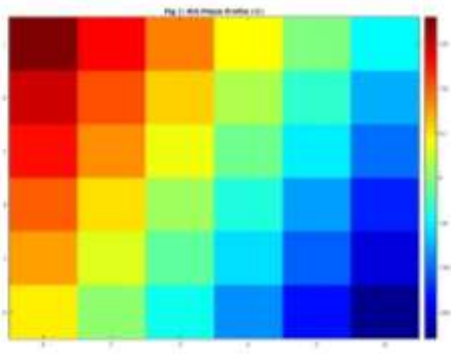
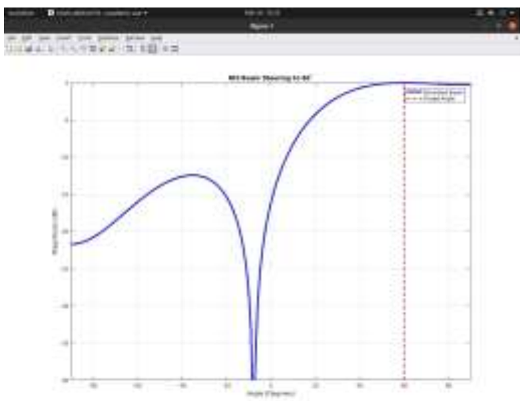
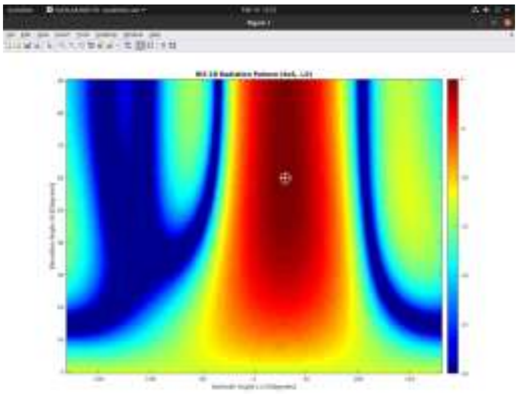


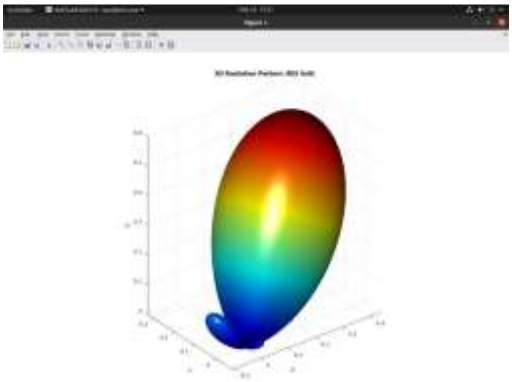
Figure 5: Phase plot for each patch



(1D)



(2D)



(3D)

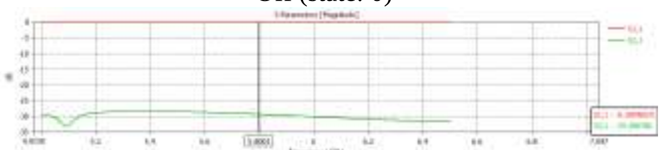
Figure 6: Radiation pattern (1D,2D,3D)

ii. CST outputs:

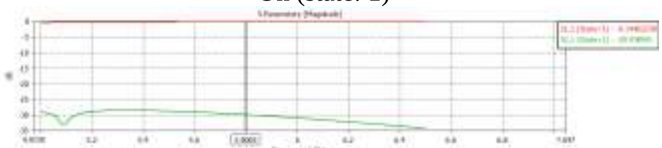
The design was simulated using the CST Studio Suite to evaluate its reflection and phase characteristics. The S-parameter magnitude plots indicate that the unit cell operates efficiently as a reflector. At the design frequency of 5.8 GHz, the reflection coefficient (S11) was approximately -0.1 dB, demonstrating minimal signal loss. The transmission coefficient (S21) remained below -29 dB, confirming that the structure effectively blocked the transmission. The phase simulation compares the response between State 0 (OFF) and State 1 (ON), characterizing the phase shift capabilities of the unit cell required for beamforming applications."

Magnitude:

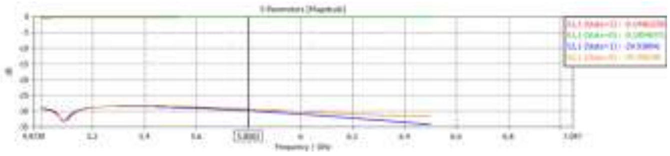
Off (state: 0)



On (state: 1)

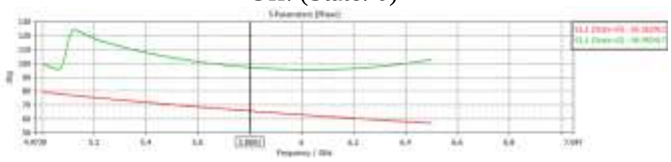


Mix:

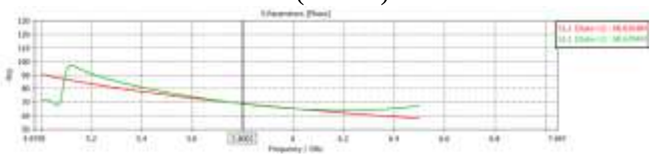


Phase:

Off: (State: 0)



On (state: 1)



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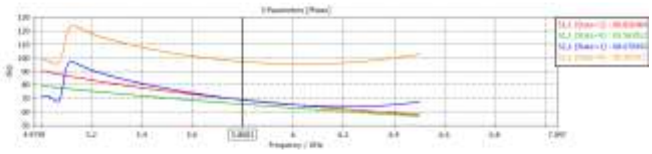

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