SHAPING FLATTENED SCATTERING PATTERNS IN BROADBAND USING PASSIVE RECONFIGURABLE INTELLIGENT SURFACES FOR INDOOR NLOS WIRELESS SIGNAL COVERAGE ENHANCEMENT

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Abstract – A novel Passive Reconfigurable Intelligent Surface (PRIS) with 100 × 100 elements, which is shaped to scatter flattened patterns in broadband, is presented to enhance the signal coverage of the indoor Non-Line-of-Sight (NLOS) area for 5G millimeter wave (mmWave) wireless communications. The signal from the base station antenna as a primary source can be deflected to the NLOS area by the proposed PRIS with a flattened scattering pattern that is insusceptible to being blocked. The broadband meta-atom, realized by the framed four arrow branches, operates from 24 GHz to 30 GHz. The genetic algorithm is applied to optimize the phase shift distribution of PRIS for a shaped pattern. Combining full-wave simulation and 3D ray-tracing simulation, the signal coverage is computed in an indoor L-shaped corridor scenario for 5G mmWave wireless communications. To verify the design, the proposed PRIS is further manufactured and tested. The experimental results reveal that the signal enhancement in the NLOS area by the proposed PRIS with the flattened scattering pattern is superior to the conventional design.

Keywords – 5G, coverage enhancement, metasurface, millimeter wave, shaped pattern

1. INTRODUCTION

5G millimeter wave (mmWave) communications can provide a larger data transmission rate and lower latency due to its huge bandwidth [1, 2]; however, it suffers from inferiorities, huge transmission loss, and nonlinear sight blocking [3]. Traditionally, more active base stations are deployed due to signals susceptible to obstacles in the indoor mmWave communication system, which means high cost and power consumption. The repeater is an economic and effective method [4, 5]. One of the repeaters is the metal reflector, such as a metal plate and ball. The high profile and inflexible wave control due to Snell's law limit its application. The other one is the dual antenna system. The signal received by the receiving antenna can be steered within a wide-angle range by the transmitting antenna. A Frequency Selective Surface (FSS) and reflect-array are also applied to indoor and outdoor communications [6-9]. A reflect-array antenna is another attractive candidate for mmWave communications with a low profile, high efficiency, flexible beam-scanning characteristics, etc., particularly for large-scale arrays [10, 11]. As can be seen, the main idea of the above two methods of a repeater is to cover a Non-Line-of-Sight (NLOS) scene into a Line-of-Sight (LOS) scene. When adopting the two types of repeaters to the indoor NLOS scene, the complicated corridors would need a large number of passive or active structures.

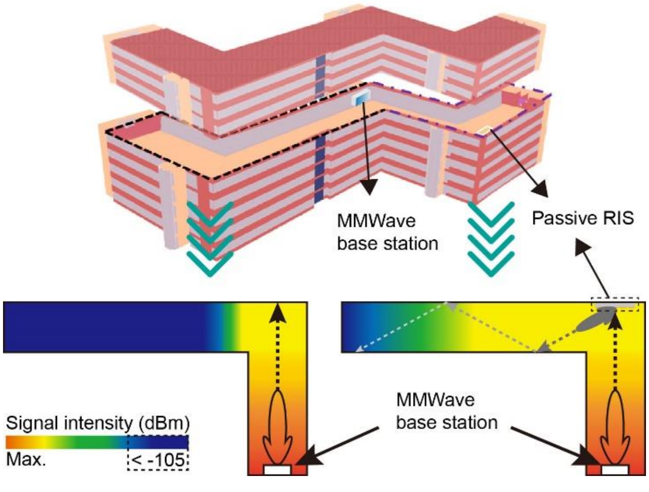


Fig. 1 – Enhancing the signal coverage in the NLOS area for the indoor L-shaped corridor by PRIS

A Metasurface (MS) is a planar artificial structure composed of subwavelength meta-atoms in an ordered sequence, offering a brand new means for mmWave communications compared with the repeaters [12-16]. The concept of a Reconfigurable Intelligent Surface (RIS), based on the MS, is then developed to control the wireless channels [17-22]. Further, by investigating the information entropy of coding MS, a new information processing system is established by digital MSs [23-29]. According to the reflected waves that can be amplified or not [30], the RIS can be divided into the Passive Reconfigurable Intelligent Surface (PRIS) [31-32] and the Active Reconfigurable Intelligent Surface (ARIS) [33-40].

By leveraging the RIS concept and hardware design, we propose a scheme to enhance the indoor NLOS signal coverage at the mmWave band, as shown in Fig. 1. Due to the limited diffraction capability of mmWaves, a typical L-shaped corridor will block the signals from the base station. If we assign a thin, low-cost, lightweight RIS on the wall of the corner to deflect the incoming signals, the original blocked NLOS area can be effectively communicated. We note that for such a ubiquitous corner the PRIS has an obvious cost advantage over the ARIS. To deflect the incident waves into a specific angle pointing to the NLOS area is a concrete idea; however, such a narrow beamwidth cannot sufficiently cover the blinded area. When there is an obstacle or people in the corridor the narrow pencil beam will be blocked to make the corridor a blind area again; therefore, the shaped beam may be a better choice [41].

Here, we present a broadband-shaped pattern PRIS for indoor mmWave communications. Compared with the conventional narrow beam design, it has a wider beamwidth in the horizontal plane. There exists countless studies on the reconfigurable meta-atom and programmable meta-atom design; therefore, for simplicity, we use a fixed-functional metasurface to demonstrate the PRIS. The following paper is organized as follows. Section 2 will introduce the broadband Framed Four ArrowBbranches (FFAB) meta-atom design, flattened pattern design, and the indoor signal coverage simulation by 3D ray-tracing technique. In Section 3, the simulation and measurement experiment results are presented to validate the effectiveness of the PRIS. By analyzing the results, it shows that the broadband-shaped-pattern PRIS is a better candidate for signal blind coverage in the door mmWave communications. Finally, the conclusion of this paper is given in Section 4.

2. BROADBAND-SHAPED-PATTERN PRIS

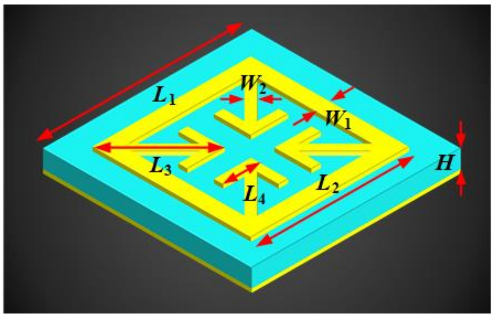


Fig. 2 – Structure of the proposed broadband FFAB meta-atom

2.1 Broadband four arrow branches element

To implement the broadband-shaped-pattern PRIS, we propose the FFAB meta-atom, as shown in Fig. 2. The meta-atom is composed of a square ring and four arrow branches on the top layer of an F4B substrate with dielectric constant 2.2 and loss tangent 0.001. The structural parameters are W_1=0.1×L_2, W_2=0.05×L_2, H=1.5mm, L_1=3.6mm, L_3=0.608×L_2, and L_4=0.277×L_2. This meta-atom is simulated with the Periodic Boundary Condition (PBC) in ANSYS Electronics Desktop 2020 and the reflection phase compensation curves versus length L_2 are reported in Fig. 3. The phase responses can cover over 360° smoothly and are linear with a constant negative slope in the range from 24.5 GHz to 29.5 GHz, which indicates that the meta-atom has a broadband characteristic. Meanwhile, due to the element's central symmetry, it can work at full-polarization modes, which is very difficult for repeaters.

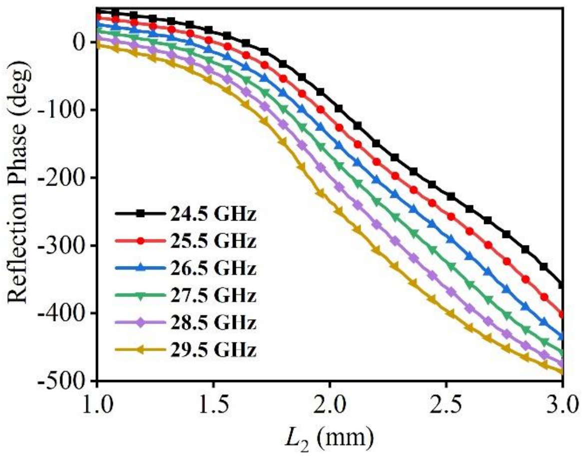
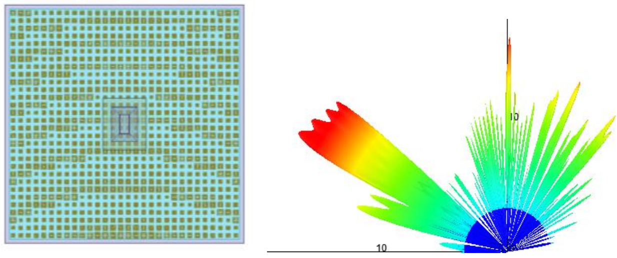


Fig. 3 – Reflection phase compensation of the broadband FFAB meta-atom

2.2 Broadband flattened beam design for indoor signal coverage

Based on the proposed broadband FFAB meta-atom, we employ the Genetic Algorithm (GA) to synthesize a flattened beam. Due to GA being mature and user-friendly, only the specific design in this work is discussed. As mentioned above, the PRIS will be deployed on the wall of the corner; thus, only the horizontal-shaped pattern is concerned. Under such an assumption, the two-dimensional array synthesis problem is reduced to a one-dimensional array synthesis problem, which is significant for the inefficient GA. Besides, we use the simulated meta-atom radiation patterns under PBC to replace the isotropic element factor in the conventional GA for array synthesis. To further simplify the optimization procedure, we use a periodic supercell that consists of four meta-atoms as an initial population condition in the GA algorithm. The target of the flattened beam is set from 48° to 62° with a 2 dB fluctuation constraint at 28 GHz.

To validate our pattern synthesis procedure, a flattened pattern PRIS with 30 × 30 meta-atoms is optimized and simulated by ANSYS Electronics Desktop 2020. The simulation model and meta-atom distribution are illustrated in Fig. 4(a). A standard horn antenna is applied as a source to excite the PRIS. We mention that the spherical phase wavefront of the horn is considered in this case; however, for a practical scenario, the incident waves are treated as quasi-plane waves. The simulated 3D radiation pattern at 28 GHz is shown in Fig. 4(b). The simulated 2D results from 24 GHz to 30 GHz are reported in Fig. 5. All the data is normalized. As can be seen, the optimization target at 28 GHz is in accordance with our goals. By observing the flattened patterns at other frequencies, we find that the wide beam coverage range moves to larger horizontal angles as the frequency decreases. This result can be explained by the fact that for a specific gradient structure a larger wavelength must correspond to a larger deflection angle to fulfill a 2π phase cycle, leading to a dispersive property.



(a) (b)

Fig. 4 – (a) Full-wave simulation model and (b) simulated flattened pattern

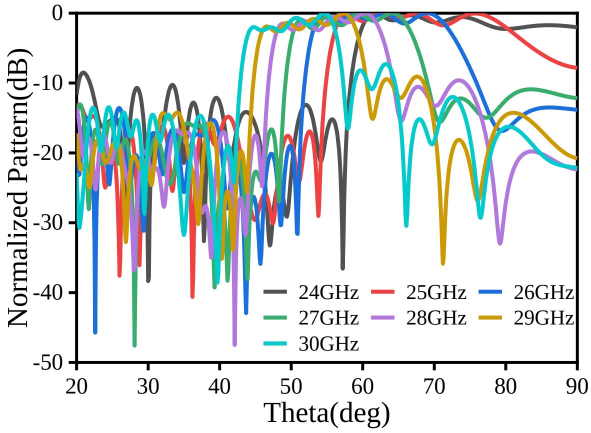


Fig. 5 – Simulated 2D broadband flattened patterns

2.3 Indoor signal coverage simulation

Furthermore, we conduct the indoor signal coverage simulation by Altair Winprop with a 3D ray-tracing technique. We note that the Customer Premises Equipment (CPE) for the simulator is our PRIS. We detail the simulation as follows. First, the received power of the PRIS which is illuminated by the base station antenna should be determined, which can be calculated by

$$P_r(\theta) = \frac{EIRP \bullet G_r \lambda^2 \bullet \overline{RCS}(\theta)}{(4\pi)^3 \left(L_t L_r \sec\theta\right)^2}, \tag{1}$$

where Effective Isotropic Radiated Power (EIRP) is the equivalent omnidirectional radiation power of an active base station, P_r is the CPE received power, G_r is the CPE receiving antenna gain, and $\overline{RCS}(\theta)$ is the Radar Cross-Section (RCS) pattern of the PRIS.

To achieve signal coverage, the angle of the shaped beam is set from 48° to 62°, and the left-side sidelobe is set to −25 dB. Then, the normalized RCS pattern can be expressed by:

$$\overline{RCS}(\theta)=\begin{cases}-25,\theta\in(-90°,45°)\\20*\log_{10}(\sec\theta)-6.57,\theta\in(48°,62°)\end{cases} \quad (2)$$

The efficiency of forwarding can be used to characterize the capability of the reflection array:

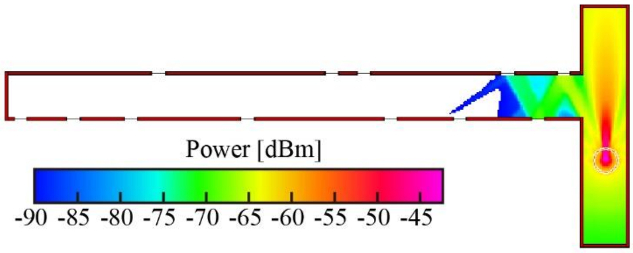
$$\varepsilon_M=\frac{\lambda^2 RCS_m}{4\pi A^2}\times\frac{\iint_{\Omega_r}\overline{RCS}(\theta,\varphi)\,d\Omega}{\iint_{4\pi}\overline{RCS}(\theta,\varphi)\,d\Omega}, \quad (3)$$

where Ω_r is the unit angle of the horizontal corridor, RCS_m is the maximum value of $\overline{RCS}(\theta)$, and A is the aperture size of 360 mm × 360 mm. The efficiency of the proposed PRIS can reach over 90%, which means that the PRIS can retransmit most of the power of the active base station to the NLOS corridor.

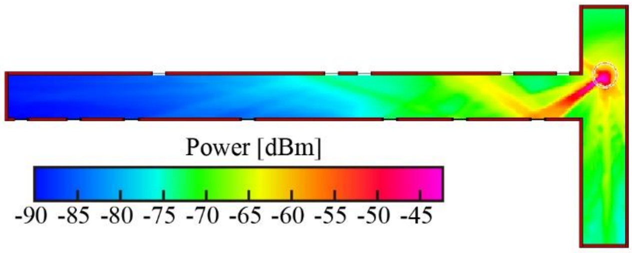
Further, to determine the signal coverage, the simulation in ANSYS Electronics Desktop and ray-tracing simulation in Altair WinProp are combined. The PRIS can be equivalent to an active base station located in the position of the corner. Considering that the incident wave is approximately a plane wave incident vertically, the equivalent omnidirectional radiation power of the equivalent active base station reads,

$$EIRP_e(\theta,\varphi)=\frac{EIRP_t\bullet RCS(\theta,\varphi)}{4\pi L_r^2}. \quad (4)$$

The signal coverage along the horizontal corridor mainly depends on the multipath propagation caused by the wall reflection. Finally, the scene of the L-shaped corridor and the equivalent active base station are modeled in the Altair WinProp with the height of 1.5 m and 20 dBm. In the model, the wall is set as a concrete wall, and the reflection loss and transmission loss are set as 9 dB and 40 dB, respectively. The number of ray-tracing is set to be 5. The simulation results with and without PRIS are given in Fig. 6 (a) and Fig. 6 (b). It can be seen that the signal intensity in the blind area is enhanced over −90 dBm with the proposed PRIS.



(a)



(b)

Fig. 6 – Indoor L-shaped corridor signal coverage simulation, (a) without and (b) with PRIS. The power level below −90 dBm is marked as white

3. MEASUREMENT AND DISCUSSION

3.1 Measurement

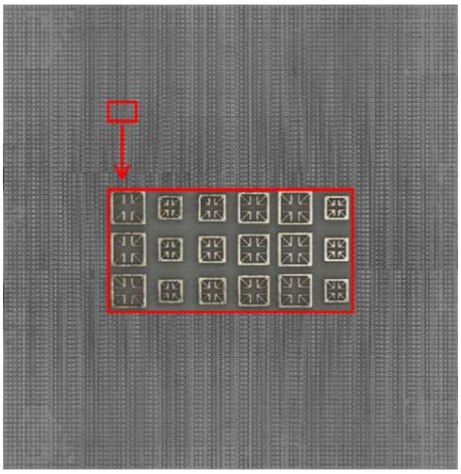


Fig. 7 – Fabricated flattened pattern PRIS

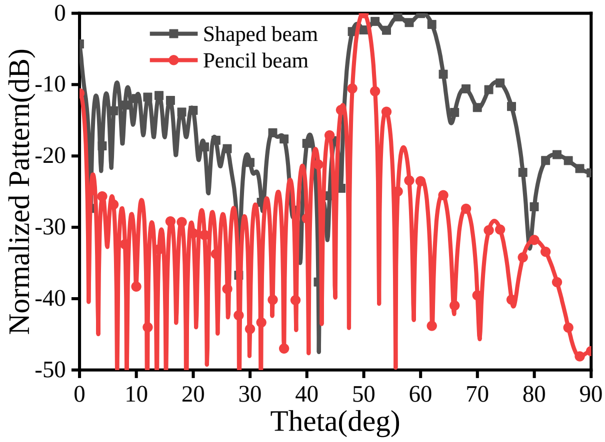


Fig. 8 – The normalized patterns of the flattened beam and pencil beam PRIS

We synthesize a PRIS containing 100 × 100 meta-atoms with a flattened pattern by GA and fabricate the prototype, as shown in Fig. 7. Before testing the PRIS with a flattened pattern in a practical environment, we measure the bistatic RCS of this PRIS. Additionally, a conventional PRIS with a pencil beam pointing at 50° is also measured. We report the measured normalized patterns of the flattened beam and pencil beam RIS in Fig. 8. From the simulation result, it can be seen that the beamwidth of the flattened beam is wider compared with the pencil beam PRIS. The signal can be transmitted into the blind area with multi-path and homogeneity characteristics to achieve better signal coverage.

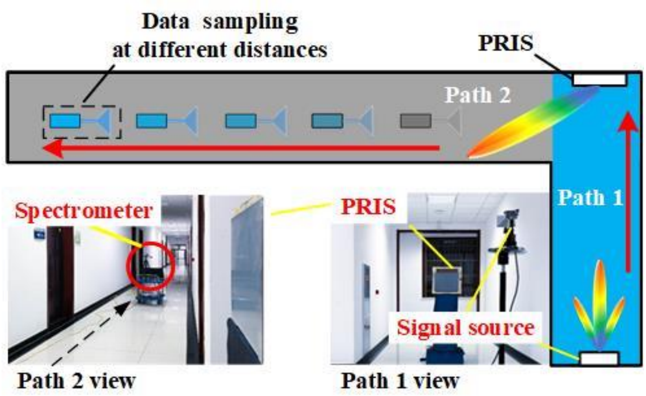


Fig. 9 – Illustration of the measurement environment

Further, we conduct a practical signal coverage enhancement experiment using the fabricated PRIS in an L-shaped corridor, as shown in Fig. 9. The measurement system consists of three parts: the signal source, the PRIS, and the data collector. The L-shaped corridor is divided into two paths. The signal source is composed of a signal generator and high gain horn in Path 1. The data collector is composed of a spectrum analyzer and low gain waveguide probe fixed on a mobile car in Path 2. The horn, PRIS, and waveguide probe are all 1.5m high, and the horn and the waveguide probe are both vertically polarized. Fig. 9 also shows the actual scene of the L-shaped corridor along Path 1 and Path 2 respectively.

The data is sampled at an interval of 90 cm along Path 2. The power of the signal generator power can be calculated by:

$$P_t = EIRP_t + IL_t - G_t \tag{5}$$

where IL_t = 5.61 dBi is the insertion loss of the cable and connector and G_t = 20.8 dBi is the gain of the horn. The receiving power at different sampling points,

$$P_r = P_{sp} + IL_r - G_r \tag{6}$$

where P_{sp} is the received power of the spectrometer, IL_r = 5.61 dBi is the insertion loss at the receiving end, and G_r = 5 dBi is the gain of the waveguide probe.

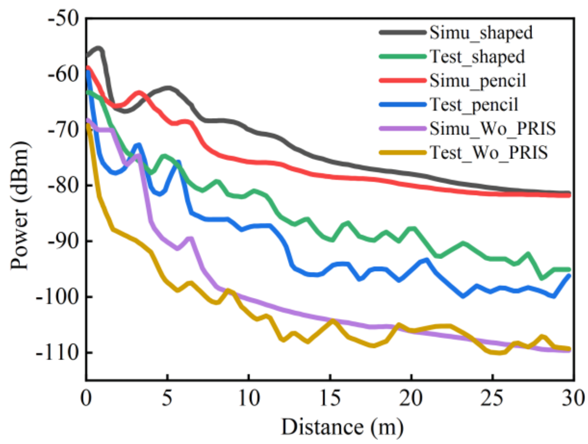


Fig. 10 – The simulation and test results of the pencil beam PRIS and flattened beam PRIS at 28GHz

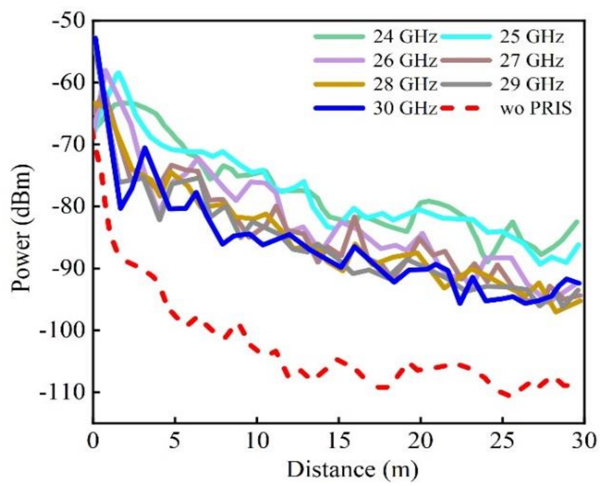


Fig. 11 – The indoor test results of the flattened-shaped PRIS

3.2 Discussion

The signal coverage simulation results in the Altair WinProp and the test results are shown in Fig. 10. From the results, the signal intensity is increased by about 20 dB and 15 dB on average at 28 GHz in the range from 5 m to 30 m along Path 2 for the flattened beam PRIS and the pencil beam PRIS, respectively. Besides, the simulated result is better than the tested ones because the NLOS scene of an L-shaped corridor in the soft WinProp doesn't exactly match the reality and the calculation process is not complicated in the actual situation.

Based on the above results, although both the pencil beam and the flattened beam PRIS can effectively enhance the indoor NLOS signal intensity, the shaped beam has a better coverage effect than the pencil beam. The simulation results are consistent with the measurement results. The effect of the signal enhancement of the shaped beam is 5 dB larger than that of the pencil beam. In addition, the shaped beam is wider and more flexible with more propagation paths, so that the signal coverage is not easily blocked by obstacles on the propagation path.

We also report the broadband signal coverage enhancement from 24 GHz to 30 GHz in Fig. 11. The signal intensity in the blind area can be improved on average by about 20 dB. The correctness of the design of the shaped pattern PRIS with the FFAB meta-atom is verified. In addition, it can be found that the signal intensity decreases with the increase of frequency, mainly because the beam direction decreases with the increase of frequency, which leads to the power of the LOS propagation decrease.

4. CONCLUSION

A novel broadband FFAB meta-atom is proposed to design a flattened pattern PRIS which is applied in indoor mmWave communications for a signal-blinded area. The reflection amplitude of the broadband FFAB element is less than 0.1 dB. The phase compensation can cover over 360°, which changes smoothly and is relatively parallel in the range from 24 GHz to 30 GHz with a full-polarization response. The GA is used to synthesize the pattern in the horizontal plane to form the shaped beam. The measured results in a practical environment indicate that signal intensity in the blind area is all greater than –90 dBm with the flattened pattern PRIS while it is about –110 dBm without PRIS. The shaped beam has a better coverage effect, 5 dB larger, than the conventional pencil beam and is wider and more flexible with more propagation paths to deal with the signal blind area problem. Through the simulation and test results, the flattened pattern PRIS is compared with a pencil beam PRIS to prove the rationality of this work.

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