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Metastructure-Enabled Radiation Pattern Unroundness Improvement for Antennas in Complex Electromagnetic Environments

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Abstract
Radiation pattern roundness is critical for achieving reliable and uniform coverage in wireless communication systems. However, antennas operating in complex environments—such as those mounted off-center on finite platforms or enclosed within dielectric covers—often suffer from pattern distortion due to asymmetric boundary conditions and unwanted guided waves. This paper investigates metastructure-based solutions to mitigate radiation pattern unroundness for both vertically and horizontally polarized antennas. For vertically polarized monopoles, impedance surfaces and Henge-like metarings are designed to suppress edge-diffracted currents and enhance omnidirectionality. For horizontally polarized dipole-based antennas, a uniaxial anisotropic meta-cover is proposed to suppress guided wave propagation within dielectric enclosures. The proposed metastructures significantly improve radiation pattern unroundness to lower than 1.9 dB and enhance coverage efficiency up to 84.7%. These methods provide a viable pathway for improving antenna performance in confined or asymmetrical settings, supporting the development of high-capacity, robust wireless networks.

Key terms
Radiation Pattern; Metamaterial; Metasurface

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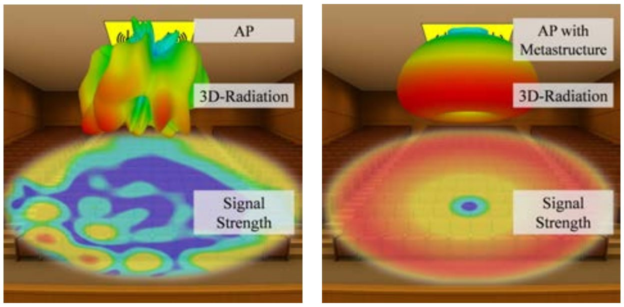
1. Introduction

Multiple-input and multiple-output (MIMO) systems, benefiting from high capacity, reliability, and high data rate, are widely applied in modern wireless networks [1, 2, 3]. In practical applications, the size of antenna platforms is often constrained by system limitations [4], [5], which becomes even more challenging for systems employing multiple antennas. Scenarios can arise where the electromagnetic environment of antennas lacks geometric symmetry, either because the antenna is mounted on an irregular platform or positioned off-center on a finite platform. In these scenarios, electromagnetic wave energy becomes concentrated in a specific area, while the energy in other regions is undesirably weakened. As illustrated in Fig. 1a, a ceiling-mounted access point (AP) is deployed at the center of an enclosed auditorium. The distorted radiation pattern radiated from the off-center antenna in the AP results in undesired radiation nulls [6] and uneven signal coverage across the audience area. In contrast, Fig. 1b illustrates an AP equipped with metastructures, which produces a highly symmetrical radiation pattern. The radiated energy is evenly distributed, leading to a smooth and centrally focused signal strength across the coverage area. Similar to other low-scattering electromagnetic environments—such as factories, exhibition centers, and stadiums—wireless devices experience significant degradation in communication performance due to radiation pattern distortions. This decline manifests in various aspects, including reduced signal-to-noise ratio (SNR), capacity, reliability, and increased latency in parts of the AP's coverage. Improved omnidirectional radiation patterns lead to significant benefits, such as maintaining robust and reliable communication channels, optimizing operational efficiency, and ensuring smooth connectivity for critical applications. Therefore, improvements in distorted radiation patterns are not only technical advancements but also vital factors in enabling the reliable and efficient operation of wireless systems in demanding industrial applications.



(a) (b)

Figure 1: Diagrams of WiFi access points (APs) mounted on the ceiling in (a) conventional environment, (b) metastructure loaded environment.

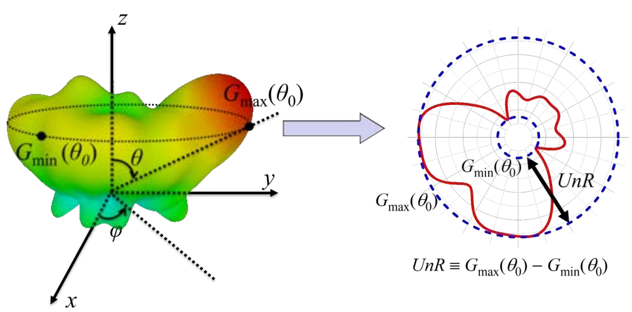


Figure 2: Illustration of the definition of UnR. (a) Three-dimensional radiation pattern of an off-center monopole. (b) Two-dimensional radiation pattern in the cut of $\theta = \theta_0$ plane.

Controlling the radiation pattern is one of the most important challenges in antenna design [7]. Besides the antenna radiation structures, the electromagnetic environments where the antennas are installed, serve as boundary conditions and have a significant influence on the radiation patterns. Significant efforts have been devoted to alleviating radiation pattern distortion caused by the environment [8], [9], [10]. For instance, the ground plane of various antennas, carrying significant surface currents and causing diffraction at the edges, severely influences the radiation patterns [11], [12], [13]. Approaches have been proposed to alleviate these diffraction by introducing resistive loading [14] and V-shape edge-grooves [15]. Besides the ground size, the antenna location on the ground plane also has a significant effect on the radiation patterns [5],[16],[17], especially for modern antenna systems with multiple antennas mounted on a finite ground. Irregular currents traveling on the ground and diffracting at the edges lead to a directional beam [18], [19] and cause pattern unroundness.

While ground currents are mainly excited by parallelly polarized magnetic fields, such as the EM fields excited by monopoles, parallelly polarized E-fields can hardly excite surface currents on the ground, thus, the radiation pattern is limitedly affected by the finite ground plane. However, the adjacent EM environments, such as an antenna cover, also influence antenna radiation patterns. Radomes (antenna covers), as essential components of nearly all antenna systems, protect antennas and surrounding electronics from adverse environmental conditions. Early research on their effect on radiation patterns has been conducted since [20], and it recently regained notice with the requirement of controlling radiation patterns for high capacity and reliability in advanced antenna systems [21].

To quantitatively evaluate the symmetry of the radiation pattern, unroundness (UnR) is defined as the maximum gain difference within the cross-section of the radiation pattern at a given angle θ_0, as shown in Fig. 2. Considering scenarios like ceiling mounted APs, users in far distance area, especially the coverage edges of the APs, suffer more from the propagating path loss. Therefore, the UnR of the antenna radiation patterns at relatively large θ angles deserves more considerations. Besides, a higher concentration of radiated energy within a conical region defined by $0^\circ \leq \theta \leq \theta_0$ is desirable, as it enhances energy delivery toward the intended user while minimizing interactions and potential interference with surrounding antenna systems. Therefore, the coverage efficiency is defined as

$$\eta_{\text{cov}} = \frac{\int_0^{2\pi} \int_0^{\theta_0} S(\theta,\phi) \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi} S(\theta,\phi) \sin\theta \, d\theta \, d\phi} \tag{1}$$

where S is the radiated power density in W/m^2. A higher value of η_{cov} indicates that more energy is directed toward the target region (e.g., toward users) with less spread into other directions, which benefits increasing signal power and reducing unwanted coupling or interference with nearby antenna systems.

In this review, the pattern distortion of both vertically and horizontally polarized antennas mounted off-center is discussed and improved by metastructures. The studies start with the pattern distortion analysis to find the causes. For vertically polarized antennas, two approaches are introduced: loading a metasurface (MTS) and a Henge-like metaring (HMR) to improve the radiation patterns. For horizontally polarized antennas, a uniaxial anisotropic metamaterial cover (meta-cover) is presented to suppress the guided wave along the conventional dielectric slabs and alleviate the pattern UnR. The analysis and designs pave the way for advanced and robust multiple antenna communication systems in micro base stations and APs in Wi-Fi 7.

2. Vertically Polarized Monopole Antennas

2.1. Distortion Analysis

Monopoles, as one of the most widely applied vertical polarized antennas with omnidirectional radiation patterns, are studied in this section. Nowadays, with the high demands of high capacity and diversity, multiple monopole antennas are mounted on a finite ground. Besides other electronic components, off-center placement is inevitable, as illustrated in Fig. 3. With the irregular electromagnetic boundary conditions, the radiation patterns are distorted, causing unstable signal connection and unreliability.

The essentials of monopole pattern distortion have been revealed [18]. The analysis is conducted by covering an absorber near the off-center monopole. As can be asserted, by fully covering the ground plane with the absorber (reserving a cylindrical

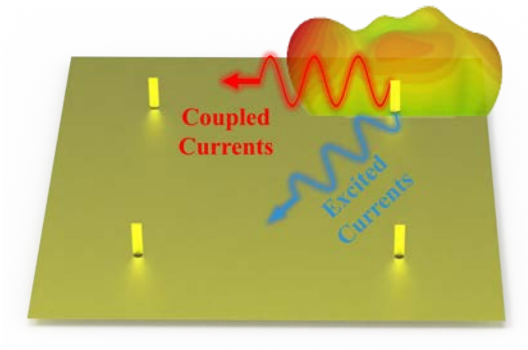


Figure 3: Illustration of multiple antennas sharing a finite ground plane.

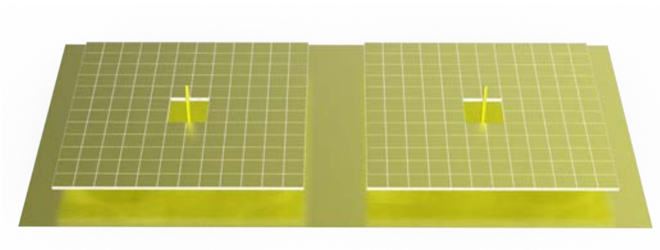


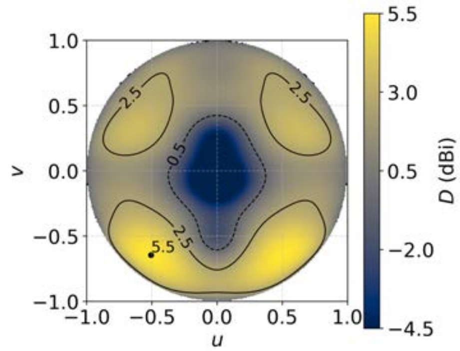
Figure 4: MTS loaded monopoles.

cavity surrounding the monopole for radiation), the corresponding radiation pattern is perfectly omnidirectional. It is caused by the circularly symmetric current distribution near the monopole. However, when only a quarter of the ground plane is covered by the absorber, it can be found that asymmetric currents flow along the ground, even though there are no electromagnetic waves propagating in the absorber. Therefore, it can be concluded that the irregular currents on the ground are caused by both bottom feed point of the monopole and the coupled fields from the radiation of the top point of the monopole.

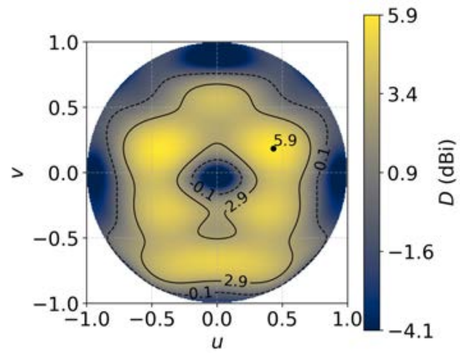
2.2. Impedance Surface

From a previous study, an MTS composed of double-layer patches is proposed to alleviate the radiation pattern distortion [22], as shown in Fig. 4. In this design, two monopole antennas are mounted off-center on a rectangular ground plane integrated with the proposed MTSs. These MTSs, as reactive impedance surfaces, effectively manipulate antenna performance by altering boundary conditions and shaping the current distribution. In [22], characteristic mode analysis (CMA) is utilized to find the desired modes of the MTS-loaded monopoles. By tuning the reactive impedance of the MTS, two modes are found to have omnidirectional radiation patterns within a wide bandwidth of 2.2 to 2.8 GHz. Besides, it can be found that both modes elevate the radiation pattern, therefore reducing the electromagnetic wave energy propagating near the ground plane. With less coupled currents on the outside ground plane and most of the energy can be radiated within the range of the MTS, the radiation patterns of the off-center monopoles on the rectangular ground become more omnidirectional, as shown in Fig. 5, where the u and v axes are defined as

$$u = \sin\theta \cos\phi \tag{2}$$



(a)



(b)

Figure 5: Radiation patterns. (a) Off-center monopoles. (b) Off-center monopoles with MTSs.

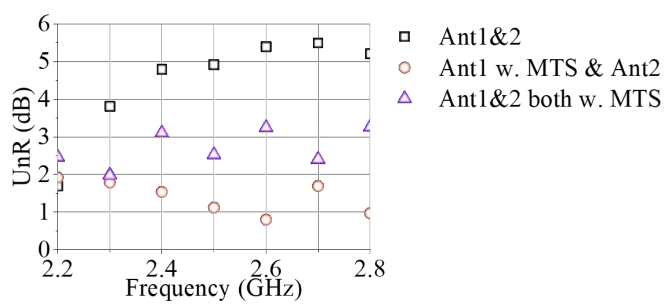


Figure 6: Simulated UnR of Ant1 in the two-monopole antenna system (Legends: Ant 1&2: two monopoles without the MTS; Ant1 w. MTS & Ant2: one monopole with MTS, the other not; Ant1 &2 both w. MTS: both monopoles with MTSs).

$$v = \sin\theta \sin\phi \tag{3}$$

The contour lines are almost round in any θ cutting planes, with more energy directs to higher elevation angles. This indicates a coverage efficiency improvement from 48% to 60% in the range of $0^\circ \leq \theta \leq 65^\circ$. The UnR in H-planes are also compared in Fig. 6. A maximum UnR is reduced in the 2.2 to 2.8 GHz band from 5.5 to 1.9 dB for two antennas mounted off-center on the rectangular ground and one with MTS and to 3.3 dB for both antennas with MTSs. The deteriorated results are caused by the coupling between adjacent MTSs.

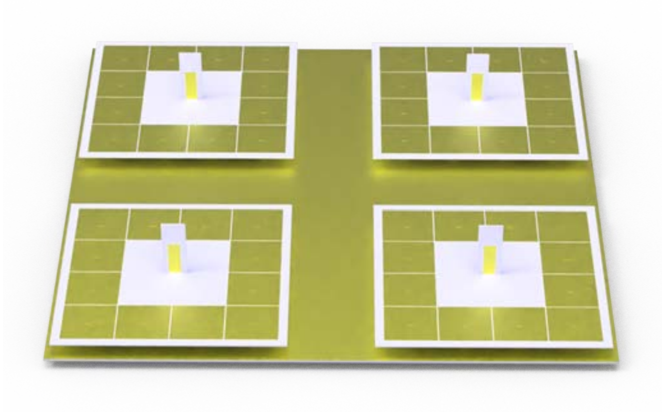
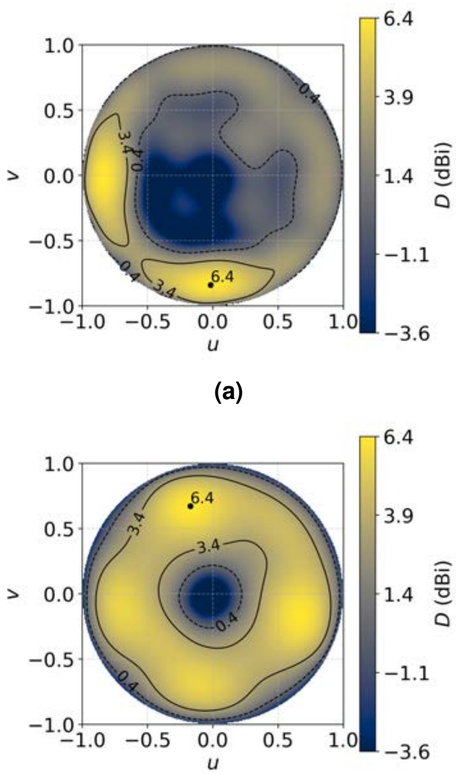


Figure 7: Configuration of four monopoles with HMRs on rectangular ground.



(a)

(b)

Figure 8: Radiation patterns. (a) Off-center monopoles. (b) Off-center monopoles with HMRs.

2.3. Henge-like Metaring

HMRs, named for their resemblance to Stonehenge, consist of an annular array of patches supported by shoring vias. As proposed in [18], they enable a more compact configuration and facilitate the integration of additional antennas on a finite ground plane, as illustrated in Fig. 7. The HMR is functioning in two ways, corresponding to the previously analyzed two currents, respectively. As a quasi-EBG, an equivalent circuit is provided, and the resonant frequency is designed to confine the currents excited by the monopole feed within the HMR, thereby suppressing current leakage and reducing edge diffraction. As a radiator, a characteristic mode with an elevated radiation pattern can be well excited. Therefore, it reduces the coupling from the radiation of the monopole and the ground plane, further localizing the currents. Besides, the HMR, as a radiator, well radiates the energy into free space, reduces reflection from EBG walls to the feed, and improves the matching. Overall, by tuning the structure parameters, the two functions can operate within the same band, and the currents both from the excited feed and those coupled from radiating waves are well alleviated outside the HMR[20].

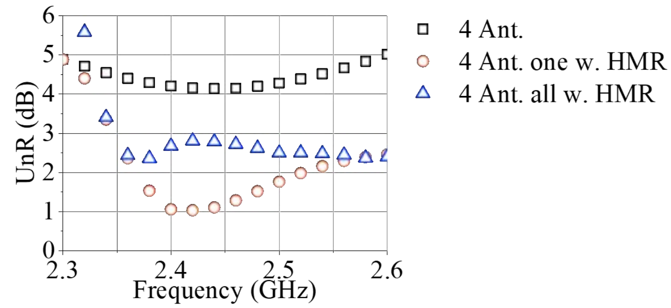


Figure 9: Simulated unR of one antenna in the four-monopole antenna system. (Legends: 4 Ant: Four monopoles off-center mounted on a ground without HMRs. 4 Ant. one w. HMR: Four monopoles off-center mounted on a ground with one of them loaded with HMR. 4 Ant. all w. HMR: Four monopoles off-center mounted on the ground with all of them loaded with HMR.)

The radiation patterns with and without the proposed HMRs are shown in Fig. 8. Similarly, the contour lines are almost round in any θ cutting planes. The radiated energy is uniformly distributed across azimuthal angles. Besides, most energy is radiated towards $\theta \leq 65°$ area with a coverage efficiency improvement from 44% to 73% in the range of $0° \leq \theta \leq 65°$. The UnR of four monopoles mounted on one finite ground plane without, with one, and all with the proposed HMRs in $\theta \cdot = 65°$ is shown in Fig. 9. Over the 2.4 to 2.5 GHz band, they achieve an improved UnR lower than 2 dB for one monopole with HMR and 3 dB for all four with HMRs. The deteriorated results are caused by the coupling between adjacent HMRs. Besides, the size of one HMR is $0.78\lambda \times 0.78\lambda$. The compactness of the proposed HMR is achieved by efficiently localizing the surface currents, which paves the way for placing multiple antennas in a limited space.

3. Horizontally Polarized Antenna

3.1. Pattern Distortion Analysis

To further increase channel diversity, orthogonally polarized antennas are commonly employed in multiple antenna systems, such as APs. Essentially different from the vertically polarized monopole antennas, horizontally polarized antennas, such as dipole-based antennas placed quarter wavelength above the ground, have limited coupling with the ground, because the vertical H-fields will not interact with the ground plane. However, antenna systems are typically protected by a dielectric cover. The nearly placed dipoles can easily excite strong guiding waves along the dielectric cover. For multiple antennas sharing a fi-

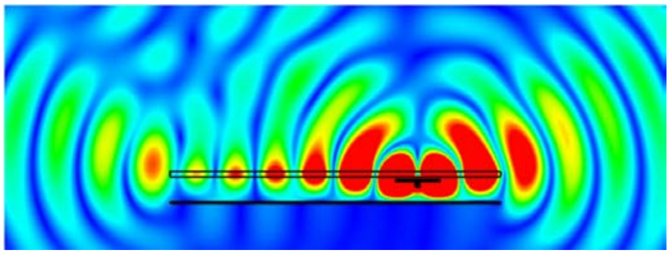


Figure 10: Field distribution of an off-center FDR with a dielectric cover.

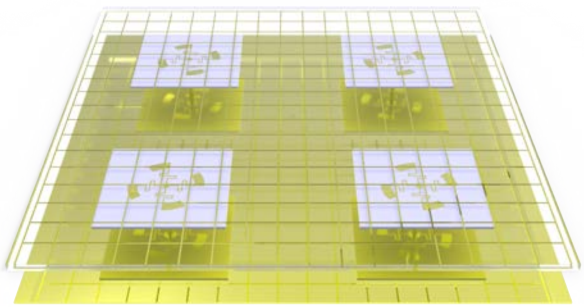


Figure 11: Configuration of four FDRs with meta-cover.

nite cover, the guided waves excited by the off-center placed antennas can cause different diffraction in the near edges and the far edges, thus distorting the radiation patterns, as shown in Fig. 10.

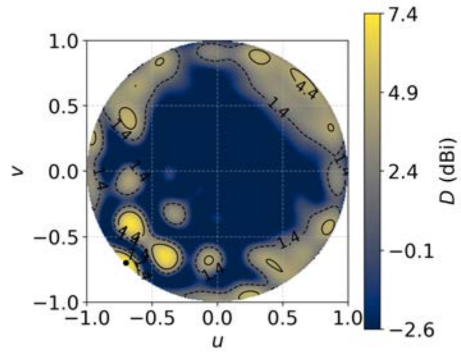
3.2. Meta-cover

For achieving horizontally polarized omnidirectional radiation patterns, four dipoles forming a ring and co-excited by one port are utilized, shorted as four-dipole ring (FDR), as shown in Fig. 11. To suppress the guided waves along the dielectric waveguide, the suppression conditions for guided waves in a uniaxial anisotropic thin slab are derived with no preconditions of material properties. For TE waves, they are concluded as [20]:

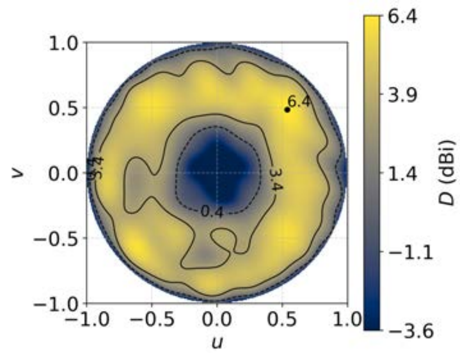
Condition 1: $\varepsilon_t \mu_z < 1, \mu_t > 0, \mu_z > 0$

Condition 2: $\varepsilon_t \mu_z < 1 - \left(\frac{\mu_z}{k_0 d}\right)^2, \mu_t < 0, \mu_z < 0, \mu_z \mu_t < 1.$

where d is the thickness of the slab. The guided waves are suppressed by satisfying any one of the conditions. Considering a wide band requirement, Condition 1 offers more potential and is set as the design guide. Besides, it is proven that the Drude model is capable of achieving a wider band suppression than the Lorentz model [20]. A Drude model-based metal mesh unit cell is designed to satisfy Condition 1 from 5 to 6 GHz. By applying the meta-cover, the corresponding radiation patterns of the FDRs are improved as shown in Fig. 11. With a conventional dielectric cover, the radiation beam is severely distorted and towards low elevation angles by the guided waves, as shown in Fig. 12a. The proposed meta-cover well suppresses the guided waves, and the radiation patterns are more omnidirectional in Fig 12b. The coverage efficiency is improved from 28% to 70% in the range of $0° \leq \theta \leq 65°$. The UnR of FDRs with and without the meta-cover in $\theta = 60°$ plane is plotted in Fig. 13.



(a)



(b)

Figure 12: Radiation patterns. (a) FDR with dielectric cover. (b) FDR with meta-cover.

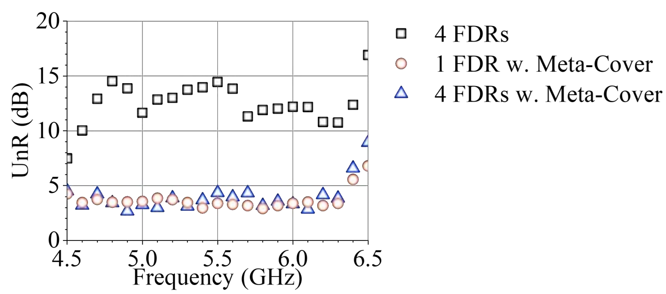


Figure 13: Simulated UnR of antennas. (Legends: 4 FDRs: Four FDRs under dielectric cover. 1 FDR w. Meta-Cover: One FDR under meta-cover. 4 FDR w. Meta-Cover: Four FDRs under meta-cover.)

The UnR is alleviated from 14.5 dB to lower than 4.3 dB in the 5 to 6 GHz band. Meanwhile, the coverage efficiency, the ratio of the radiated power within $0° \leq \theta \leq 75°$ to the total radiated power is improved from 42.4% to 84.7%.

4. Conclusion

This review has demonstrated three approaches for improving the radiation pattern roundness of both vertically positioned monopole and horizontally positioned dipole antennas in complex environments. For vertically polarized monopole antennas, the study has revealed that the distortion is caused by both excited currents from the feed of the monopole and the induced currents by the radiation from the top of the monopole. By incorporating MTSs and HMRs, the radiation has been effectively localized and reshaped into more omnidirectional patterns, mitigating the distortion. For horizontally polarized dipole-type antennas, such as the four-dipole ring, the guided wave in the dielectric cover causes the pattern distortion. Guided wave suppression conditions in uniaxial anisotropic metamaterials have been derived to guide the meta-cover design. By applying the meta-cover for suppressing the guided waves, the radiation pattern has been improved to omnidirectional. Overall, comprehensive analysis and various methods in this review have provided solutions for radiation pattern control within multiple-antenna systems within complex electromagnetic environments.

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