Electromagnetic Diffusion of a Wall with Modified Checkerboard Pattern

Yasutaka Murakami a), Jerdvisanop Chakarothai, and Katsumi Fujii
National Institute of Information and Communications Technology
4-2-1, Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan
a) y_murakami@nict.go.jp

Abstract: Recently, fifth-generation (5G) wireless communication systems have been spreading rapidly, and 5G mobile phone services started in 2020 in Japan. 5G wireless communication systems can provide not only greater capacities and higher speeds, but also ultrahigh-reliability, low latency, and multi-connectivity. Electromagnetic (EM) waves in the 28 GHz band are also used for 5G communications. At such high frequencies, only a few paths can reach a receiving antenna, owing to the high propagation loss and high directivity of antennas used. Consequently, when an obstacle, such as office partitions, exists in a room, the quality of wireless communications deteriorates abruptly in the blocked region. In this paper, we confirm the improvement in the diffusion characteristics of an EM scattering wall with a modified checkerboard pattern. We design and optimize an EM scattering wall that exhibits a wide EM diffusion characteristic for both TE and TM polarizations of incident fields.

Keywords: Fifth-generation wireless communications system, EM wave scattering, Checkerboard pattern

Classification: Electromagnetic compatibility (EMC)

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1 Introduction

Fifth-generation (5G) wireless communication systems have been employed and their uses in many applications are spreading rapidly. In Japan, 5G mobile phone services started in 2020 [1]. As well as having higher capacities and speeds, 5G wireless communication systems can provide ultrahigh reliability, low latency, and multi-connectivity. In 5G wireless communication systems, EM waves in the 28 GHz band are used. At such a high frequency, only a few paths can reach a receiving antenna owing to the high propagation loss and high directivity of antennas. Consequently, when an obstacle, such as office partitions, exists in a room, the quality of wireless communications deteriorates abruptly in the blocked region [2, 3].

Recently, we have proposed an optimized EM scattering wall for improving wireless communication quality in the 28 GHz band [4, 5]. The EM scattering wall is designed to diffuse EM waves impinging on the wall. Therefore, the number of propagation paths can be effectively increased by using the proposed EM scattering wall. However, it was optimized for only one incident polarization of EM waves in our previous design [5].

| $K, L$ | 6, 6 |
|---|---|
| $S_x, S_y$ | 200 mm, 200 mm |
| 10PBW (Transmitting antenna) | $15^\circ$ |

Fig. 1. Configuration of checkerboard structure.
In this paper, we design an optimized EM scattering wall for a wide diffusion of EM waves in both TE and TM polarizations. The diffusion characteristics of the modified checkerboard pattern wall with a two-direction array structure are also revealed [6].

2 Structure of EM scattering wall and checkerboard structure

The proposed EM scattering wall with a size of \(S_x \times S_y\) for the wide diffusion of EM waves with two incident polarizations is composed of two sets of metal square with a \(\lambda/4\) height difference to realize reflection phases of 0° and 180° as shown in Fig. 1.

Here, the metal squares with two different heights are alternately arranged in a checkerboard pattern [6]. Then, the 3D scattering pattern \(E(\theta, \phi)\) of the designed structure with \(K \times L\) elements is numerically obtained by using an approximate equation based on antenna array theory [5].

\[
E(\theta, \phi) = D(\theta, \phi)G(\theta, \phi).
\]

(1)

Here, \(D(\theta, \phi)\) and \(G(\theta, \phi)\) are the array and element factors, respectively [7]. \(\delta_a\) is the reflection phase of the element, which is equal to 0° or 180°. \(\delta_b\) and \(\delta_c\) are the coefficients determined from the position and the characteristics of the radiation pattern of the transmitting antenna, respectively. Here, a horn antenna is assumed as the transmitting antenna. \(A_{kl}\) is the incident amplitude from the EM source to the surface of the \((k,l)\)th element. \(d_x\) and \(d_y\) are the distance from the reference element to the \((k,l)\)th element along the \(x\)- and \(y\)-axes. Moreover, \(M_\theta(\theta, \phi)\) and \(M_\phi(\theta, \phi)\) are the coefficients of the scattering patterns for the two metals [7]. In ref. [5], we have already confirmed that the scattering patterns calculated by Eq. (1) are in good agreements with the experiment results.

In this paper, the scattering pattern \(E(\theta, \phi)\) is evaluated using the diffusion coefficient \(\zeta\) [8], given by

\[
\zeta = \frac{\left(\sum_{i=1}^{n} \sum_{j=1}^{m} |E(\theta_i, \phi_j)|^2 - \sum_{i=1}^{n} \left|\sum_{j=1}^{m} E(\theta_i, \phi_j)\right|^2\right)}{(n \times m - 1) \sum_{i=1}^{n} \left|\sum_{j=1}^{m} E(\theta_i, \phi_j)\right|^2}.
\]

(2)

where, \(n\) and \(m\) are the division numbers of the scattering pattern elevation and azimuth angles in the evaluation, respectively. When the scattering pattern is omnidirectional, \(\zeta = 1.0\), and \(\zeta = 0\) for perfect specular reflection. In Eq. (2), \(\zeta\) is averaged over all incident angles coming from \(\theta_{inc}\) direction ranging from -60° to 60° and \(\phi_{inc}\) direction ranging from -45° to 45° with 5° steps.

3 Diffusion coefficient of checkerboard structure

In this chapter, scattering patterns and diffusion coefficients are calculated by Eq. (1) and (2), respectively. Fig. 2 shows the 3D scattering pattern of the original checkerboard structure with 6×6 divisions. Figs. 2 (a) and (b) respectively shows the results for the original checkerboard and the modified checkerboard when the
phase of the element #8 is inverted. In Fig. 2, the antenna distance $P$ is infinity (or plane wave incidence) and the incident angle $(\theta_{\text{inc}}, \phi_{\text{inc}})$ is equal to $(0^\circ, 0^\circ)$. From Fig. 2(a), it is seen that there are multiple sharp and strong scattered beams. This is because the phase difference between adjacent elements is constant, thus the scattered waves intensify each other in a specific direction. On the other hand, the central scattering intensity distribution changes in the case of the modified checkerboard pattern with the inverted phase of element #8.

Fig. 3 shows the analysis results of the designed structure having $6 \times 6$ elements with different distances from the transmitting antenna to the element surface with respect to the index of the element whose reflection phase is inverted from $0^\circ$ to $180^\circ$. In Fig. 3, the horizontal and vertical axes indicate the index number of phase-inverted element and the diffusion coefficient normalized by that of the original checkerboard structure (index number #0 in Fig. 1) without the phase-inverted element, respectively. Therefore, if the normalized diffusion coefficient exceeds 1.0, it means that the designed structure with the phase inverted element can improve the diffusion coefficient. In Fig. 3(d), the results of the full-wave simulation obtained by using the moment method are also shown as a comparison of analysis results derived from Eq. (1). In the simulation, the normalized diffusion coefficient (one point) is calculated from analyses of 494 different models with
varied incident angle of plane wave. From Fig. 3, the diffusion coefficient varies on the location of the phase-inverted element. From Figs. 3 (a)–(c), for the horn antenna incidence, the diffusion coefficient shows little improvement when the phase of one of the elements is inverted. However, for the plane wave incidence, where the transmitting antenna distance is considered infinity (Fig. 3(d)), the diffusion coefficient is significantly improved by about 40% when the phase of element #8 or #11, near the center of the checkerboard, is inverted. Moreover, the results using Eq. (1) and those by full-wave simulation generally agree, the improvement of the diffusion coefficient is, therefore, obvious when the phase of one of the elements is inverted. The improvement of the diffusion coefficient is expected to be due to the change in relationship between the phase differences among adjacent elements. The reason why the diffusion coefficient changed by the antenna distance will be studied in the future.

4 Conclusion

We have shown that the EM diffusion characteristics of a checkerboard structure can be significantly improved by changing the reflection phase of one element in the checkerboard pattern from 0 to 180°. As a result, it is shown that the diffusion coefficient is changed by the phase inversion of particular elements. Moreover, in the case of the modified checkerboard structure with 6×6 divisions, the diffusion coefficient can be significantly improved by about 40% by inverting the phase of a single element.