Design of electromagnetic scattering wall using genetic algorithm

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Abstract: 5G wireless communications use electromagnetic (EM) waves in the 28 GHz band, and the EM waves radiated from high-directivity (gain) antennas are hence scattered in a specular direction by walls. If there are obstructions between the transmitting and receiving antennas, the wireless communication quality is deteriorated since the receiver can receive neither direct waves nor reflected waves. In this paper, an EM scattering wall is designed by applying array antenna theory to improve the wireless communication quality. Moreover, the optimum configuration of the EM scattering wall is designed by using the genetic algorithm without a large amount of calculation by an EM simulator.

Keywords: Array antenna theory, Genetic algorithm, Scattering wall, 5G
Classification: Electromagnetic Compatibility (EMC)

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1 Introduction
5G wireless communications use electromagnetic (EM) waves in the 28 GHz band [1]. High-directivity (gain) antennas are used in this frequency band and EM waves radiated from the antennas are hence scattered in a specular direction by walls. If there are obstructions between the transmitting and receiving antennas, wireless communication quality is deteriorated since the receiver can receive neither direct waves nor reflected waves [2]. Improving wireless communication quality using a metamaterial (MTM) reflector was previously researched [3, 4]. This is because the EM wave power from an incident angle ($\theta_i$) can be transferred to the desired angle ($\theta_r$) by an MTM reflector. However, the MTM surface has the problems of high dielectric loss and the need for a machine tool high fabrication accuracy.

Therefore, we propose an EM scattering wall with a wide-angle scattering pattern and evaluate its characteristics. The EM scattering wall is designed using array antenna theory [5]. Moreover, the optimum configuration of the EM scattering wall is designed using the genetic algorithm (GA) [6].

2 Design of scattering wall
In this paper, we propose an EM scattering wall that reflects EM waves with a wider angle than that of a perfect electric conductor (PEC) of the same size. By the EM scattering wall, the number of propagation paths is increased and, therefore, the wireless communication quality is improved by waves scattered from the EM scattering wall reaching the receiving antenna.

2.1 Configuration and scattering pattern
The proposed EM scattering wall is composed of two metal plates with different heights as shown in Fig. 1(a). The reflection phases of the plates at the reference surface are 0° and 180°, which are realized by changing the height of one of the metal plates by $\lambda/4$, generating a phase difference of $\lambda/2$ when the EM waves propagate back to the reference surface. One of the metal plates is $\lambda/4$ below the reference surface. Therefore, phase rotation occurs as a result of the path length difference. This configuration has the advantages of simple design and material availability.

The scattering pattern from the EM scattering wall is calculated by applying array antenna theory. To calculate the pattern, the EM scattering wall is replaced with an array antenna of $K$ elements, with a distance between elements of $\Delta d_k = w$ (which is also the width of each metal plate). Considering the location of the transmitting antenna, the scattering pattern $E'_{\text{sum}}(\theta)$ of the EM scattering wall is derived as follows:
Here, $\delta_k$ is the phase shift of the reflection phase of the plate on the reference surface. $\delta_k^{\text{feed}}$ and $\delta_k^{\text{inc}}$ are the phase shifts required when the location of the transmitting antenna is considered. $A_k$ and $A_k^{\text{feed}}$ are the amplitude level on the surface of the metal plate and the incidence power level to $k$th element from transmitting antenna, respectively.

### 2.2 Evaluation value

The scattering pattern $E'_{\text{sum}}(\theta)$ is evaluated using the diffusion coefficient [7]

$$\zeta = \frac{\sum_{i=1}^{n} |E'_{\text{sum}}(\theta_i)|^2 - \sum_{i=1}^{n} |E'_{\text{sum}}(\theta_i)|^2}{(n-1)\sum_{i=1}^{n} |E'_{\text{sum}}(\theta_i)|^2}.$$  

Here, $\theta_i$ and $n$ are the $i$th angle and the number of divisions of the obtained scattering patterns, respectively. The scattering pattern of the EM scattering wall is isotropic in the case of $\zeta = 0$, and perfect specular reflection occurs in the case of $\zeta = 1$. In this study, to realize wide-angle scattering pattern, the EM scattering wall must be composed of the combination of metal plates giving the maximum diffusion coefficient.

### 2.3 Design using GA

To design the optimum EM scattering wall with the maximum diffusion coefficient using Eqs. (1) and (2), it is necessary to perform the calculation for all combinations of metal plates. However, the required number of trials to design the optimal configuration increases exponentially as the number of metal plates increases. Therefore, to design the optimum configuration and to decrease the number of trials, the EM scattering wall is designed using the GA. Fig. 1(b) shows the algorithm used to design the optimal EM scattering wall. In the GA, we regard two metal plates of different reflection phases as the gene code $[180^\circ, 0^\circ] = [0,1]$. Here, the choice of methods is the elite choice and roulette choice, the crossover method is two-point crossover, and the mutation rate is 75%. In addition, the number of samples is almost $1.6 \times (\text{number of elements} K)$.

![Fig. 1.](image-url) (a) Configuration of EM scattering wall and (b) flowchart of design of EM scattering wall using GA.
3 Result of design of scattering wall

Fig. 2(a) shows an example of updates of the diffusion coefficient up to the 40th generation obtained using the GA. In Fig. 2(a), the incident angle $\theta_{\text{inc}}$, the number of elements $K$, the element width $w$, and the distance $L$ between the receiving antenna and the scattering wall are $0^\circ$, $10$, $2.0\lambda$, and $660$ mm ($61.6\lambda$), respectively. The vertical axis is the diffusion coefficient normalized by the maximum value obtained from performing the calculation for all combinations of metal plates ($2^{10}=1,024$ combinations). From Fig. 2(a), it is found that the desired EM scattering wall with wide-angle scattering can be designed, since the normalized diffusion coefficient converges to $1.0$ as the number of generations is increased. The required number of trials to obtain the quasi-optimum configuration using the GA is expressed as \( \text{number of generations} \times \text{number of samples} \), i.e., $40 \times 16 = 640$, which is $37.5\%$ fewer trials than the total numbers of combinations.

Fig. 2(b) shows the diffusion coefficient obtained for different numbers of elements $K$. In Fig. 2(b), the incident angle $\theta_{\text{inc}}$ and the EM scattering wall size $S$ are $0^\circ - 60^\circ$ and $20\lambda$, respectively. The vertical axes are the diffusion coefficient and the percentage decrease in the number of trials, where

$$\text{Decrease in number of trials} = \left(1 - \frac{\text{Number of trials GA}}{\text{Total number of combinations}}\right) \times 100\%.$$  \hspace{1cm} (3)

From Fig. 2(b), it is found that a quasi-optimal EM scattering wall with a high diffusion coefficient can be designed by using the GA. Moreover, the rate of decrease in the number of trials increases with the number of elements (metal plates). Also, the number of the trials in the GA can be decreased by almost $99.9\%$ in the case of $20$ elements. Therefore, it is considered that the EM scattering wall can be designed effectively by using the GA.

Next, Figs. 3(a) and (b) show the configuration of the designed EM scattering wall designed using the GA in the cases of $K = 10$ and $20$ elements, and Figs. 3(c) and (d) show the corresponding scattering patterns, respectively. The solid and dashed lines show the results of using array antenna theory (Eq. (1)) and the EM simulator based on the moment method (MOM), respectively. From Figs. 3(c) and
(d), it is found that the scattering patterns obtained by array antenna theory show good agreement with the MoM results. Moreover, the designed EM scattering wall can realize wide-angle scattering characteristics. Here, the average values of the diffusion coefficients in the cases of $K = 10$ and 20 are 0.59 and 0.73, respectively. These values are higher than that of 0.23 for a PEC of the same size. In addition,

![Diagram](image1)

![Diagram](image2)

**Fig. 3.** (a) Configuration of scattering wall $K = 10$ and (b) $K = 20$. (c) Scattering pattern and $K = 10$ and (d) $K = 20$. (e) Experimental setup and measurement result ($K = 10$) of (f) $\theta_{\text{inc.}} = 0^\circ$, (g) -15°, and (h) -30°.
Fig. 3(e) shows the measurement configuration and Figs. 3(f) to (h) show the measurement result of the designed EM scattering wall (K = 10). Here, the EM scattering wall is made of a duralumin board (an alloy of aluminum and copper). It should be noted that we cannot perform measurements in the overlapping range of the two antennas. The time gate function of the network analyzer is used to suppress direct mutual coupling between the two antennas. Figs. 3(f) to (h) show the obtained scattering patterns for three incident angles, where the red lines and blue broken lines show the results of array antenna theory and experiments, respectively. The scattering patterns obtained from the array antenna theory are in good agreement with the experimental results. However, there are some differences for the incident angle of -30°. This is because the thickness of the metal plate is not considered in array antenna theory, which only includes the reflection phase of the surface. From the experimental results, it is considered that the proposed design is effective.

4 Conclusion

We have presented an EM scattering wall that can be used to improve wireless communication quality. The EM scattering wall was designed by applying array antenna theory, and an optimum configuration of the EM scattering wall was designed using by the GA without a large amount of calculation by an EM simulator. The designed EM scattering realized the characteristics of wide-angle scattering and a scattering pattern obtained from the proposal design was in good agreement with experimental results. When the number of elements of the EM scattering wall was 20, The number of trials in the GA was decreased almost 99.9 % compared with total number of combinations of elements by metal plate. Therefore, it is considered that an EM scattering wall can be designed effectively by using the GA.