URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

An Overview On the Optimization of Beam-Steering Metasurfaces

Khushboo Singh[1], Muhammad U. Afzal[1], and Karu P. Esselle[1]
(1) School of Electrical and Data Engineering, University of Technology, Sydney, NSW 2007, Australia

Abstract

This paper presents an evaluative summary of the optimization algorithms based methods reported to improve the efficiency of Near-Field Meta-Steering (NFMS) systems. These methods are classified into two categories based on their objective functions. The first category includes methods, which defined their objective function in terms of directivity pattern and desired radiation pattern mask, to either optimize long 1D arrays of phase-shifting cells in the metasurfaces or optimize the amplitude distribution of the feeding base antenna. The second category includes those methods, which used Floquet modes to only optimize the periodically repeating group of cells in the metasurfaces. Each of these is discussed briefly, followed by a detailed discussion on their advantage and relevance. The periodic nature of PGMs is used to create a computationally inexpensive equivalent model, which is then used for optimization purposes. Both methods substantially improve the performance of PGM-based beam-steering systems.

1 Introduction

Near-Field Meta-Steering (NFMS) has gained considerable attention among researchers and industry due to its suitability in existing and upcoming wireless applications. The NFMS antenna systems are based on the concept of near-field phase transformation [1, 2, 3]. They are designed using a pair of closely spaced, independently rotating, thin PGMs placed in the near field of a medium-to-high gain fixed base antenna as shown in Fig. 1 [4, 5]. Beam steering within a conical volume in the far field is achieved by physically rotating the pair of metasurfaces. In a classical NFMS system design, the two PGMs are identical and have the same phase gradients. However, this is not mandatory, and the two metasurfaces may have different phase gradients.

The PGMs are electrically large, planar structures composed of periodically repeating supercells along x- and y-direction to create a gradient phase in the electric field at the output of the metasurfaces to tilt the antenna beam. The supercell comprises an array of phase-shifting cells, each corresponding to a unique transmission phase and high transmission magnitude. These cells are carefully picked from a database that stores transmission phases and magnitudes of several such phase-shifting-cells simulated assuming infinite periodicity along x- and y-direction. This assumption is practically infeasible since the neighboring cells in a supercell are non-identical [4]. The transmission phase and amplitude of constituent cells vary when placed in a supercell due to variation in mutual coupling. The metasurface near-field phase profile becomes non-linear, resulting in undesired sidelobes in the far field of a PGM-based beam-steering system. The inherent challenge with the periodic arrangement of cells in PGMs is that it generates grating lobes, which violate regulation masks and reduce system efficiency.

The PGMs are locally non-periodic with sub-wavelength metallic features. Hence, they cannot be analyzed using the typical approaches such as transmission-line modeling and unit cell optimization method [6]. Also, accurate analytical models for PGMs are not available. Thus, their optimization needs to be performed using a full-wave EM simulation model. The population-based global optimization algorithms popularly known as evolutionary algorithms (EAs) are known to handle complex problems elegantly [7, 8, 9]. Usually, PGMs for practical high-gain antennas have an electrically large aperture and a large number of spatially distributed small metallic features, which makes their design and optimization computationally prohibitive and intricately challenging. Performing population-based global optimization on such electrically large simulation models is infeasible. Instead, researchers focused on using the periodicity of PGMs to obtain equivalent simulation model that closely represent the actual metasurface model but are computationally far less expensive to optimize. An efficient

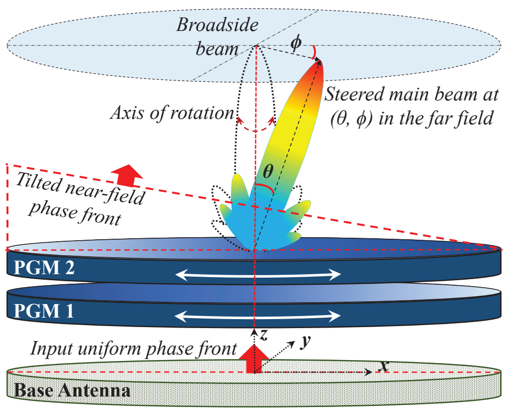

Figure 1. Configuration of an NFMS system.

beam-steering system must steer the desired/main beam with minimum reduction in directivity and simultaneously maintain low side-lobe levels (SLLs) at all times, to reduce signal leakage and avoid interference. This paper presents a critical overview on numerical optimization based research reported on improving the efficiency and enhancing the far-field performance of the PGMs for NFMS systems.

2 Radiation Pattern-based Optimization

Beam-steering systems must abide by/comply with regulatory standards such as FCC and ETSI, which require them to maintain their directivity pattern below a specified radiation pattern mask. The radiation pattern-based PGM optimization aims to suppress the sidelobes and fit the radiation pattern below a specified mask. The cost function (*FF*) is defined as:

$$FF = \sum_{\theta=-180}^{180} (min(0,(Mask(\theta) - Directivity(\theta))))^2. \quad (1)$$

The value of FF is evaluated for all elevation angles θ from $-180°$ to $180°$ with a step of $1°$. The expression (1) ensures that when the directivity pattern is above the mask, their squared difference is contributed towards the FF, and when it is below the mask, there is no contribution. The optimizer aims to minimize the FF, which minimizes the difference between the mask and directivity pattern when the pattern violates the mask.

The optimization of full metasurface structure using sophisticated EAs would be time and memory consuming (in fact, it is computationally infeasible and would need supercomputers with high-end processors). To reduce the computation complexity, a simplified equivalent model, as shown in Fig. 2 was proposed [10]. It is derived from original metasurface and has same *x-axis* dimension (L = 345 mm). The *y-axis* dimension (W = 7.5 mm) is kept as small as the dimension of constituent unit cell. Appropriate boundary conditions are provided to mimic the complete 2D metasurface. In CST MWS, the boundary was set to "E(t) = 0" along *y-axis* to implement periodicity and to model the truncation along *x-axis* the boundary was set to "open add space". This model also accounts for the mutual coupling between the metallic patches. Since this simplified

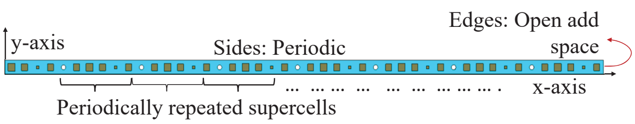

Figure 2. Simplified equivalent model of a metasurface with boundary conditions specified to mimic a full 2D metasurface.

structure still falls under high-mesh geometry ($\geq$ 800000 hexahedrons), the batch processing needs to be avoided. Thus, a generalized version of cross-entropy (CE) algorithm called as one-candidate-per-generation variant of CE (OV-CE) method was implemented where each candidate is evaluated one by one [7, 10]. Details of OV-CE method are available in [7].

Two example implementation of radiation pattern-based PGM optimization using OV-CE algorithm are discussed in following subsections. The PGM-based beam-steering systems considered in these examples must comply with the Federal Communications Commission (FCC) mask (25.209) for Ka-band applications. The *Mask* function is expressed in equation (2) that specifies a maximum desired gain (in **dBi**) for different values of elevation angle θ ranging from $-180°$ to $180°$, when the peak radiation is in the broadside direction. There is a maximum permissible level of gain corresponding to each angle θ. When the beam is steered δ degrees, the mask is shifted such that the center is in the beam's peak radiation direction and the $|\theta|$ in (2) can be replaced by ($|\theta| - \delta$), to express the *Mask* function for the tilted beam.

$$Mask = \begin{cases} 24.6\ \textbf{dBi}, & 1.5° < |\theta| \leq 7° \\ 7.8\ \textbf{dBi}, & 7° < |\theta| \leq 9.2° \\ 8\ \textbf{dBi}, & 9.2° < |\theta| \leq 19.1° \\ 0\ \textbf{dBi}, & 19.1° < |\theta| \leq 180° \end{cases} \quad (2)$$

The OV-CE algorithm was implemented with a goal to minimize the cost function defined in (1).

2.1 Optimizing PGMs for Fixed Feed

The concept of radiation pattern-based PGM optimization has been implemented in [10]. The metallic patch dimensions and hole radius are used as optimization variables. The radius of hole along with the side-lengths of patches in one supercell constitute a design vector of length 11. The fixed parameters in the metasurface design include the aperture size ($23\lambda_0 \times 23\lambda_0$), cell size ($d = \lambda_0/2$) and permittivity of the dielectric substrate ($\varepsilon_r = 2.2$). The equivalent model (Fig. 2) is fed with a uniform plane wave illumination from one wavelength below the metasurface. For the ease of fabrication and to circumvent physically impractical/abstract designs, the minimum and maximum bounds for patch dimensions are kept as 0.5 mm and 7.5 mm (equal to the size of a single cell), respectively, and the radius of the hole is bounded between 0.5 mm and 3.5 mm.

Each evaluation in CST MWS time-domain solver took approximately 28 minutes on an Intel Core i7-6700 CPU@ 3.4 GHz processor with a 64 GB RAM. The total time required for optimization with 959 function evaluations was 447 hours and 48 minutes. Adaptive meshing was implemented to accommodate the patch geometry changes at every function evaluation. A full PGM was designed using optimized design variables. The directivity pattern of initial PGM violated the FCC mask at four different locations ($\theta = -80°, -20°, 0°, 40°$) in the visible range of θ. After optimization, most of the sidelobes were suppressed, and the directivity pattern violated the FCC mask only at two locations, $\theta = -40^\circ$ by 3.5 dB and $\theta = 40^\circ$ by 0.5 dB. The overall SLL has reduced to -17 dB, which shows a 4 dB improvement compared to -13 dB SLL in the initial design.

2.2 Optimizing Amplitude Distribution of the Feed for Fixed PGM

A beam-steering PGM illuminated using an array of small dipoles located one wavelength below is optimized using a radiation pattern-based optimization approach in [7]. The simplified equivalent model shown in Fig. 2 is excited using an array of small dipoles with half-wavelength spacing, backed by a metallic ground plane. The Chebyshev or Taylor amplitude tapering commonly used for SLL suppression in a phased array has asymmetric distribution with a bell-shaped profile. To follow a similar pattern, we used 23 different amplitude excitations and repeated in a mirror symmetry once to cover the entire aperture composed of 46 elements in the x-direction, as shown in Fig. 2.

The complete optimization with 23 design variables took 198 hours and 4 minutes. It performed a total of 566 function evaluations before the termination criterion was satisfied, and the algorithm stopped. The optimization process suppressed all the undesired sidelobes below the FCC mask except for the one sidelobe located at -20°. The directivity of the optimized PGM has reduced by 1.4 dB. This reduction can be attributed to the tapering introduced in the feed array.

3 Floquet-Mode-based Optimization

The second optimization routine is a physics-based approach that derives its concept from Floquet mode analysis of periodic structures [11, 12]. The supercells repeat periodically in a 2D plane to form a PGM. They are analogous to one period of a diffraction grating. Therefore, a PGM essentially mimics the behavior of a blazed grating. The number and location of transmitted diffraction modes are governed by the diffraction grating equation expressed as:

$$L(\sin\theta_m - \sin\theta_i) = m\lambda, \tag{3}$$

where θ_m is the angle of diffraction, θ_i is the angle of incidence, m is the order of diffraction, λ is the wavelength, and L is the length of the supercell (the period of the grating). This concept was further extended to improve the performance of NFMS systems in [4, 13] by optimizing a smaller periodic supercell, thus reducing computational cost and saving time and resources. It was revealed that steeper PGMs are better since they have fewer undesired grating lobes, which is mathematically verified by diffraction grating equation (3).

To perform Floquet-mode analysis the supercell was simulated in CST MWS under periodic boundary conditions and excited with a broadside TE(00) mode propagating along the z-axis. An excellent correlation between the magnitudes and directions of the Floquet modes and the dominant lobes in the far-field pattern (main lobe and grating lobes) of a PGM (obtained using array factor multiplication) was observed. The knowledge of the positions and relative magnitudes of the desired beam and the grating lobes in the far-field was used in conjunction with a multi-objective particle swarm optimization (PSO) to selectively target the strong grating lobes that correspond to the modes with high magnitude in a supercell Floquet mode analysis. The objective function (FF) in equation (4) is defined as a weighted sum of objectives mentioned above to selectively suppress the unwanted grating lobes and enhance the desired mode:

$$\begin{aligned} FF = {} & [w_m\{\max(0,(-0.1-DM))\}]^2 + \\ & \sum_{i=1}^{9}[w_i\{\max(0,(UDM_i-(-35)))\}]^2, \end{aligned} \tag{4}$$

where w_m is the weight associated with the desired mode (DM), and w_i are the weights associated with the undesired modes (UDM). The value of w_m is fixed to 20, and w_i can vary between 1 to 19. The weights are higher for the UDMs with higher magnitude and vice-versa. The algorithm aims to minimize the FF thereby enhancing the desired modes and reducing the undesired ones. The corresponding changes in the supercell Floquet modes reflect in the far-field performance of the PGMs.

The Floquet mode analysis based PGM optimization was implemented in [4] to reduce all grating lobes in an NFMS system to a level below -20 dB for all beam directions, without applying any amplitude tapering to the aperture field. Multi-objective PSO used to reduce these lobes while simultaneously ensuring high transmission through every cell in the metasurface.

4 Discussion

Controlling SLLs in a beam-steering PGM is a critical and challenging task. Various intrinsic factors contribute towards the grating lobes, and the complexity of metasurface structures makes it practically impossible to have abrupt control over them. The ultimate aim of optimizing a PGM-based beam-steering systems is to achieve a clean far-field radiation pattern free of undesired grating lobes and sidelobes. Both optimization approaches discussed in the paper benefit from the periodic nature of PGMs and use smaller and simpler equivalent simulation models to reduce the computation complexity multiple folds. This makes the application of population based EAs feasible. These optimization methods also take into account the variations in mutual coupling between dissimilar adjacent cells in a supercell.

The radiation pattern-based PGM optimization method does not indulge into the physics of the simulation model and considers the problem as a black box optimization. The algorithm collects the output data from the simulation model and performs post processing to calculate the value of cost function and determines if a given set of input design variables is optimum. Once the optimization converges, the design variables corresponding to the minimum cost function value is used to construct a full PGM.

The Floquet mode-based PGM optimization method is based on the principal of diffraction grating. The algorithm aims to increase the energy transmitted to the desired Floquet mode and meticulously targets to suppress the undesired modes by adding weights to each undesired dominant grating mode based on their magnitudes (higher the magnitude higher is the weight and vice-versa). Due to the intrinsic correlation between the Floquet modes of periodic supercells and the far-field pattern predicted for PGM (using CST array calculator that implements array factor multiplication), the changes in Floquet modes reflect in the dominant lobes that appear in the far-field radiation pattern. Thus, by controlling the Floquet mode magnitudes the radiation performance of PGMs is optimized without having to perform full-wave simulations on electrically large surfaces.

Both optimization routines work well for PGM-based beam-steering systems. However, the radiation pattern-based method requires more time, memory, and computational resources compared to Floquet mode-based optimization routine. The results predicted by the radiation pattern-based optimization method is much closer to reality since the equivalent model applies periodicity assumption only along the y-direction. The x-direction boundary conditions are the same as the original metasurface. The Floquet mode-based optimization routine assumes periodicity in both x-and y-direction. Although, it dramatically reduces the computation time while they do not predict the far-field pattern of a finite-sized PGM with great accuracy. If the PGM aperture is significantly large, then Floquet mode-based optimization is an optimum choice. For smaller aperture, radiation pattern-based optimization provides better-predicted results.

References

[1] M. U. Afzal and K. P. Esselle, “Steering the beam of medium-to-high gain antennas using near-field phase transformation,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 4, pp. 1680–1690, 2017.

[2] ——, “High-gain beam steering by near-field phase transformation-an overview,” in *2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*. IEEE, 2018, pp. 1447–1448.

[3] M. U. Afzal, L. Matekovits, K. P. Esselle, and A. Lalbakhsh, “Beam-scanning antenna based on near-electric field phase transformation and refraction of electromagnetic wave through dielectric structures,” *IEEE Access*, vol. 8, pp. 199 242–199 253, 2020.

[4] K. Singh, M. U. Afzal, M. Kovaleva, and K. P. Esselle, “Controlling the most significant grating lobes in two-dimensional beam-steering systems with phase-gradient metasurfaces,” *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 1389–1401, 2019.

[5] M. U. Afzal, K. P. Esselle, and A. Lalbakhsh, “A system-level overview of near-field meta-steering,” in *2020 XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio Science*. IEEE, pp. 1–4.

[6] H. Nematollahi, J.-J. Laurin, J. Page, and J. A. Encinar, “Design of broadband transmitarray unit cells with comparative study of different numbers of layers,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1473–1481, 2015.

[7] K. Singh, M. U. Afzal, D. Bulger, M. Kovaleva, and K. P. Esselle, “Optimizing amplitude distribution in a feed array to control side-lobe levels of a beam-steering metasurface,” in *2019 URSI International Symposium on Electromagnetic Theory (EMTS)*. IEEE, 2019, pp. 1–4.

[8] M. Kovaleva, D. Bulger, and K. P. Esselle, “Comparative study of optimization algorithms on the design of broadband antennas,” *IEEE Journal on Multiscale and Multiphysics Computational Techniques*, vol. 5, pp. 89–98, 2020.

[9] M. Kovaleva, D. Bulger, B. A. Zeb, and K. P. Esselle, “Cross-entropy method for electromagnetic optimization with constraints and mixed variables,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 10, pp. 5532–5540, 2017.

[10] K. Singh, M. U. Afzal, D. Bulger, M. Kovaleva, and K. P. Esselle, “Optimization of beam-steering metasurfaces using modified cross-entropy algorithm,” in *2019 URSI International Symposium on Electromagnetic Theory (EMTS)*. IEEE, 2019, pp. 1–4.

[11] J. E. Harvey and C. L. Vernold, “Description of diffraction grating behavior in direction cosine space,” *Applied optics*, vol. 37, no. 34, pp. 8158–8159, 1998.

[12] F. D. Tart and J. E. Harvey, “Alignment theory and practice for diffraction grating rhombs,” in *Optical alignment II*, vol. 483. International Society for Optics and Photonics, 1984, pp. 2–9.

[13] K. Singh, M. U. Afzal, K. P. Esselle, and M. Kovaleva, “Towards decreasing side lobes produced by near-field phase gradient metasurfaces,” in *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*. IEEE, 2019, pp. 1207–1208.