Trade-offs in Multifaceted Passive Electromagnetic Deflector for the 60 GHz Frequency Band

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Abstract—The MATLAB formulation for the parametric geometry of the deflector configuration has been validated with CST MWS simulations, after incorporation of the radiation pattern, polarization mismatch and the transmission coefficient of the deflector elements in the former. A close agreement between the extended MATLAB formulation and CST MWS simulations gives confidence in the former to study the trade-offs in a passive electromagnetic deflector using the multi-objective genetic algorithm approach; the latter being too computationally intensive for the same. The effect of fabrication misalignment among different layers of the deflector's PCB and angle of incidence on the transmission coefficient of the deflector is also investigated.

I. INTRODUCTION

The 60 GHz frequency band has inspired the realization of next-generation wireless broadband communication systems, due to the availability of 7-9 GHz unlicensed bandwidth. However, to utilize the full potential of this band, low-cost antenna solutions with wide angular coverage are desirable for applications like wireless gigabit ethernet, wireless HDTV, telecom backhaul, etc.

A passive electromagnetic deflector for the 60 GHz frequency band, presented in [1], [2], offers a possible low-cost alternative for the wide angular coverage. In a deflector-based configuration, the source antenna array focuses power on each face of a multifaceted passive deflector which bends this electromagnetic wave towards directions that are out of reach of the source itself [3], as delineated in Fig. 1. The design details of a planar source antenna array (57.5-65.0 GHz) and a passive deflector (57-63 GHz) are reported in [3] and [1], respectively. Each deflector face consists of a group of elements with a phase-shift among them. The design of three different deflector elements, which realize a relative phase shift of -120°, 0°, and +120° for the 57-63 GHz frequency band, is described in [1]. The three elements are placed in an alternating order along one direction with identical elements along the other direction, thereby deflecting an incident wave by 34°. The 0° deflector comprises 0° phase shifting elements along both directions. The above-mentioned deflectors are designed so that the polarization of the emitted wave is orthogonal to the polarization of the incident wave.

An important aspect of the deflector based configuration is the transmission coefficient and its dependence on angle of incidence and fabrication misalignment among different layers of the deflector’s PCB. Furthermore, the multifaceted deflector based configuration is very large in terms of wavelength, so it is difficult to analyze it with commercially-available 3D electromagnetic tools. Although the simulation tools, for instance CST MWS, take into account most of the electromagnetic effects, it is computationally very intensive and CST MWS requires more than 13 million mesh cells, for the simple set-up of a broadside deflector facet and a 6-element source antenna array. Moreover, for the whole configuration, the freedom of parametrization and creation of different scenarios by phase-shift adjustments is not possible with commercially available EM tools. A generalized MATLAB formulation of the parametric multifaceted deflector configuration is therefore desirable. However, the formulation should be complete enough to establish the viability of the multifaceted deflector based configuration.

Section II presents the effect of misalignment and angle of incidence on the deflector’s transmission coefficient. The extended MATLAB formulation and its validation with CST MWS simulations is described in Section III. Section IV highlights the use of the MATLAB formulation and the genetic algorithm approach to investigate different scenarios and trade-offs in a passive electromagnetic deflector. Finally, the conclusions are drawn in Section V.

II. DEFLECTOR’S TRANSMISSION COEFFICIENT

An important aspect of the passive electromagnetic deflector is the determination of its transmission properties for the entire band of operation (57-63 GHz). The possible linkage of the degradation of deflector’s transmission coefficient (tx. coeff) to the fabrication misalignment among different layers of the PCB samples [2], will be validated in this section. Moreover, it is also desirable to investigate the effect of the incident wave angle on the transmission performance of the misaligned deflector. The frequency domain solver of CST MWS software has been used for the said purpose. The unit cell boundary conditions in the directions of periodicity (x- and y-directions) set up Floquet port excitations in the positive and negative z-directions with parameterized incident angle of the plane wave. The default Floquet port settings excite two plane waves with orthogonal electric fields. Co-polar and cross-polar coupling between the modes, for both reflection and transmission, are represented in terms of S-parameters. Since the polarization of the emitted wave by the deflector plate is orthogonal to the polarization of the incident wave, the cross-polarised transmis-
Fig. 1: Multifaceted passive electromagnetic deflector: half truncated icosahedral deflector

The transmission between Floquet modes 2 and 1 at ports $Z_{\text{max}}$ and $Z_{\text{min}}$ ($S_{\text{max}}(2)Z_{\text{max}}(1)$) is determined. The set-up enables to simulate the effect of fabrication misalignment on the transmission coefficient of the deflector. The misalignment introduced due to fabrication limitations for a $0^\circ$ deflector is found to be about 230 $\mu$m from X-ray photographs (Fig. 2). A comparison of the measured transmission coefficient for a $0^\circ$ deflector is made with the CST simulated transmission coefficient for both the aligned and the misaligned $0^\circ$ deflectors. Figure 3a shows a close agreement of the transmission coefficient between the measured and CST simulated misaligned $0^\circ$ deflector, thereby explaining the degradation of deflector’s transmission coefficient. It is worth-mentioning that the PCB manufacturers can achieve the alignment tolerance of 100 $\mu$m for the said deflector, resulting in transmission loss of almost 1 dB in the 57-63 GHz frequency band. The dependence of $0^\circ$ deflector’s transmission coefficient on angle of incidence ($-15^\circ, 0^\circ$ and $+15^\circ$) is simulated and the results are highlighted in Fig. 3b.

III. GENERALIZED MATLAB FORMULATION AND VALIDATION WITH CST MWS

A. MATLAB Formulation

The MATLAB formulation for the simple parametric geometry of the broadside and skewed deflector facets, presented in [2], is extended to incorporate the radiation pattern, polarization mismatch and the transmission coefficient of the deflector elements. The MATLAB code, however, does not include the formulation of mutual coupling effects between the deflector elements.

The far-field electric field of the source antenna array is expressed as

$$E_{\text{source}}(r, \theta, \phi) = \exp(-jkr)E_i(r, \theta, \phi)e_s(\theta, \phi) \sum_{i=1}^{N} c_s^{(j(\beta_{\text{source}}+kr_i))}$$

where $E_i(r, \theta, \phi)$ is the amplitude of the electric field intensity of each antenna element $i$ at the far-field distance $r$, $k = \frac{2\pi}{\lambda}$ is the free-space phase constant, $\hat{r} = \sin \theta \cos \phi \hat{x} + \sin \theta \sin \phi \hat{y} + \cos \theta \hat{z}$ is a unit vector in the direction of the far-field observation point, $\hat{r}_i$ is a position vector from the origin $O$ to the $i_{th}$ element of $N$-element source antenna array, $e_s(\theta, \phi)$ is the polarization vector of the incident wave and $\beta_{\text{source}}$ is the
phase shift applied by each element to steer the beam. The gain of the source antenna array can be calculated as

$$G_{\text{source}}(\theta, \phi) = \varepsilon_{\text{srad}} r^2 \frac{|\vec{E}_{\text{source}}(r, \theta, \phi)|^2}{4\pi}$$  \tag{2}

where $\varepsilon_{\text{srad}}$ is the radiation efficiency and $P_{\text{source}}$ is the total radiated power of the source antenna array which is given by

$$P_{\text{source}} = \frac{1}{2\eta_0} \int_0^{2\pi} \int_0^\pi |\vec{E}_{\text{source}}(r, \theta, \phi)|^2 r^2 \sin \theta d\theta d\phi$$  \tag{3}

The directivity of each deflector element $D_d(\theta, \phi)$ on the reception and the transmission side is modelled as $D_d(\theta, \phi) = 2(m+1) \cos^m \theta$, where $m \geq 0$, $0 \leq \theta \leq \frac{\pi}{2}$ and $0 \leq \phi < 2\pi$.

The available power $P_{rd}$ of each deflector element having the polarization-phase vector of $\vec{E}_{\text{source}}$ on the reception side, in $xyz$-space can be written in terms of the power flow density $S(r_d, \theta_d, \phi_d)$ of the incident plane wave towards the direction of the deflector element, the effective area of the deflector element $A_e(\theta_d, \phi_d)$ and the polarization mismatch factor $e_{pol}$. Hence,

$$P_{rd} = S(r_d, \theta_d, \phi_d) A_e(\theta_d, \phi_d) \cos \theta_{sa} e_{pol}$$  \tag{4}

$$S(r_d, \theta_d, \phi_d) = \frac{|\vec{E}_{\text{source}}(r_d, \theta_d, \phi_d)|^2}{2\eta_0}$$  \tag{5}

where $\theta_{sa}$ is the angle between the radial unit-vector of the incident power flow density and the unit-vector normal to the deflecting element surface. The effective area of each deflector element is

$$A_e(\theta_d, \phi_d) = \frac{\lambda^2}{4\pi} D_d(\theta_d, \phi_d) \varepsilon_{\text{rad}}$$  \tag{6}

and the polarization mismatch factor $e_{pol}$ equals

$$e_{pol} = |\vec{e}_s \cdot \vec{e}_{dr}|^2$$  \tag{7}

The power of each deflector element on the transmission side $P_{td}$ is related to the transmission coefficient $|S_{21}|$ as $P_{td} = |S_{21}|^2$. The transmission coefficient is a function of angle of incidence and can be determined from CST simulations or measurements for a specific deflector. The amplitude of the electric-field intensity of each deflector element $E_{di}(r, \theta, \phi)$ at the far-field distance $r$ is expressed as

$$E_{di}(r, \theta, \phi) = \sqrt{\frac{2 \eta_0 P_{td} D_d(\theta, \phi)}{4\pi r^2}}$$  \tag{8}

The far-field electric field of the whole deflector $E_{def}(r, \theta, \phi)$ containing $T$ deflector elements is given by

$$E_{def}(r, \theta, \phi) = \exp(-jkr) \sum_{d=1}^{T} E_{di}(r, \theta, \phi) e^{j(\beta_d r + k r_d + k r_{dr}))}$$  \tag{9}

where $\vec{e}_{di}$ is the polarization vector of the deflector elements on the transmission side. The phase shift $\beta_d$ is adjusted to provide the deflection in the desired plane and $r_d$ is the path length from the source antenna array located at the origin to each deflector element. The gain $G_{def}(\theta, \phi)$ of the whole deflector in the upper half-space ($0 \leq \theta \leq \frac{\pi}{2}$ and $0 \leq \phi < 2\pi$) can be calculated as

$$G_{def}(\theta, \phi) = \varepsilon_{\text{srad}} r^2 \frac{|\vec{E}_{def}(r, \theta, \phi)|^2}{4\pi}$$  \tag{10}

B. Validation with CST MWS

A comparison of the deflector-based configuration, comprising different dimensions of a single 0° or 34° deflector facet with varying heights h and a 6-element hexagonal source antenna array, is made with extensive CST MWS simulations to validate the extended MATLAB formulation. The following points are worth-mentioning with regard to the comparison between MATLAB formulation and CST MWS simulation results:

- Since the MATLAB formulation does not include diffraction from the deflector’s facet edges, a fair comparison with the CST simulated model is only possible, when the deflector facet is surrounded by an RF absorber or an infinite metal plate. The theoretical limitation of an ideal absorber for the minimum reflection while producing the maximum attenuation can be expressed by the relation $\varepsilon^* = \mu^*$, where $\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon'_r(1 - j \tan \delta_e)$ is the complex relative dielectric permittivity, with $\tan \delta_e$ the electric loss tangent and $\mu^* = \mu'_r - j\mu'' = \mu'_r(1 - j \tan \delta_m)$ is the complex relative magnetic permeability, with $\tan \delta_m$ the magnetic loss tangent [4]. CST MWS has been used to simulate the transmission and reflection coefficient of an ideal absorber (same simulation setup as mentioned in Section II) by parameterizing the real permittivity/permittivity and the loss tangent (electric/magnetic) at a particular frequency. For $\varepsilon^*_r = 1.9 - 5.51j$, the reflection and transmission coefficients are below -46 dB and -37 dB, respectively for the 57-65 GHz frequency band. However, the use of this absorber for surrounding the deflector facet increases the mesh cells of the simulation set-up to the extent that the simulation is aborted; an infinite metal plate has been used instead. The CST model of a 0° (9 x 9) broadside deflector facet surrounded by an infinite metal plate and a 6-element source antenna array is highlighted in Fig. 4.

- The directivity $D_d(\theta, \phi)$ of the deflector element, presented in [1] is approximated by $4 \cos \theta$, as concluded from 3D EM simulations. Moreover, the radiation pattern of a 6-element hexagonal source antenna array, generated by CST MWS simulations has been used in the MATLAB formulation.

- CST MWS simulations use the total radiated power of the whole configuration as a normalization factor for the calculation of the gain. Since MATLAB formulation computes the gain of the whole deflector in the upper
half-space \((0 \leq \theta \leq \frac{\pi}{2} \text{ and } 0 \leq \phi < 2\pi)\) with \(P_{\text{source}}\) as a normalization factor (eq. 10), the same has been used for computing the gain from the CST MWS results. The transmission coefficient of each deflector element is determined from the simulation results presented in Section II. The angle of incidence dependence is incorporated for each deflector element as per its angle in the \(\theta\)-domain, using extrapolation and interpolation.

Figure 5 shows CST MWS and MATLAB simulated gain patterns in the \(\phi = 90^\circ\) and \(\phi = 0^\circ\) planes at 60 GHz, for the case when a \(0^\circ\) deflector plate \((T_{\text{col}} = 9, T_{\text{row}} = 9, dx = 0.6\lambda_0, dy = 0.64\lambda_0)\) is excited by a 6-element hexagonal source antenna array from the broadside direction. The height \(h\) between the center of the broadside deflector facet and the source antenna array center (at the origin \(O\)) is taken to be \(4.4\lambda_0\). The results of CST simulation and the extended MATLAB formulation are in close agreement; the difference for the maximum value of the deflector’s gain is within 1 dB, which is attributed to the mathematical approximation of the radiation pattern of the deflector element in the MATLAB formulation. The same observations have been made when different dimensions of a single \(0^\circ\) or \(34^\circ\) deflector facet with varying heights \(h\) are used, thereby validating the extended MATLAB formulation.

![Fig. 4: CST model of a 6-element source antenna array and a \(0^\circ\) (9 x 9) broadside deflector facet for the 60 GHz band](image)

**IV. INVESTIGATION OF TRADE-OFFS**

In Section III, it is shown that the results of the CST simulation and the extended MATLAB formulation are in close agreement, thereby giving confidence in the analysis of the multifaceted deflector configuration with the latter. It also gives the freedom of parametrization and creation of different scenarios for the whole configuration by phase-shift adjustments, which is not possible with commercially available EM tools. Multi-objective optimization using genetic algorithm (GA) can be employed for the investigation of different scenarios. Multi-objective optimization is concerned with the minimization of a vector of objectives \(F(v)\) that can be the subject of a number of constraints or bounds. In principle, multi-objective optimization is different than single-objective optimization; the latter can be accomplished by using weights for different objective functions, leading to a single solution. In case of multiple objectives, there may not exist one solution, which is the best with respect to all objectives. A general goal in multi-objective optimization is to use Pareto optimization, which means to optimize all the objectives simultaneously giving them equal importance. If none of the objective function values can be further improved without impairing the value of at least one objective for a given solution then this solution is Pareto-optimal and belongs to the set of non-dominated solutions which is called Pareto front; from this set of non-dominated solutions optimal designs that provide a suitable compromise between the objectives for the desired constraints can be realized [5]. The multi-objective genetic algorithm solver `gamultiobj` of MATLAB’s Optimization Toolbox has been used for the said purpose.

For a multifaceted deflector configuration, it is desirable to have a \(-3\) dB cross-over point (both in the \(\theta\)- and the \(\phi\)-domain) for the beams from the consecutive deflector facets, when the steerable source antenna array focuses power on different facets having an appropriate polynomial phase distribution. This section presents directivity pattern of a broadside deflector facet with pre-fixed amplitude distribution, quadratic phase distribution, desired side-lobe and ripple levels, using multi-objective optimization method based on genetic algorithm. The mathematical statement of the optimization process is: Find \(\min_v F(v) \rightarrow y_{\text{opt}}\), where \(F(v)\) is a vector of objective functions of parameter variables \(v\). For the case of a broadside

![Fig. 5: Comparison of gain (dBi) of 6-element source antenna array (left) and a \(0^\circ\) (9 x 9) deflector (right) for \(\phi = 90^\circ\) plane (red) and \(\phi = 0^\circ\) plane (blue) at 60 GHz; MATLAB formulation (dash) and CST simulation (solid)](image)
deflector facet,
\[
F_1(\psi) = \sum_{\theta = 0}^{\pm 90^\circ} (P_{\text{def}}(\theta, \phi) + 10), \text{ if } P_{\text{def}}(\theta, \phi) > P_d \delta_2, \text{ otherwise } 0
\]
\[
F_2(\psi) = \sum_{\theta = 0}^{\pm 30^\circ} (|P_{\text{def}}(\theta, \phi)|), \text{ if } |P_{\text{def}}(\theta, \phi)| > P_d \delta_3, \text{ otherwise } 0
\]
where \(P_{\text{def}}(\theta, \phi) = 10 \log(D_{\text{def}}(\theta, \phi))_{\text{normalized}}\) (normalization is with respect to the maximum value; \(D_{\text{def}}(\theta, \phi)\) is determined using the mathematical formulation in Section II, with radiation efficiency equal to 1), \(P_d \delta_2 = -10\) dB is the desired maximum side-lobe level from \(\theta = \pm 31^\circ \pm 90^\circ\) and \(P_d \delta_3 = 0.5\) dB is the maximum desired ripple in the main beam \((0^\circ \pm 30^\circ)\). The quadratic phase distribution \(\alpha(i_{\text{col/row}})\) for the deflector elements (spacing among the elements \(d_x = d_y = 0.63\lambda_0\)) along \(T_{\text{row}}\) and \(T_{\text{col}}\) is given by \(k_{2(\text{col/row})} = 2\cos(\phi)\), where \(k_{2(\text{col/row})}\) is the coefficient of a quadratic polynomial measured in radians or degrees and \(i_{\text{col/row}}\) is the argument which refers to the position of a given element along \(T_{\text{row}}\) and \(T_{\text{col}}\). The phase shift \(\beta_d\) (eq. 9) includes the quadratic phase distribution and the compensation of \(kr_d\) for each deflector element. The vector \(v\) consists of \(T_{\text{row}}, T_{\text{col}}, h\) and \(k_{2(\text{col/row})}\). The use of \(k_{2(\text{col/row})}\) reduces the number of variables to be optimized to two, instead of the case when phases of all the elements are optimized separately. The scenario for a 6-element hexagonal source antenna array and the broadband deflector facet with quadratic phase distribution has been simulated using gamultiobj. Multi-objective optimization requires a decision making process as there is not a single solution but a set of non-dominated solutions, out of which the best must be chosen. The polynomial phase distribution function \(\alpha(i_{\text{col/row}})\) (degrees) and directivity pattern (dBi) at 60 GHz for the said scenario against the selected solution of the obtained variables \((T_{\text{row}} = T_{\text{col}} = 5, h = 3.1229\lambda_0\) and \(k_{2(\text{col/row})}\) (rad) = 0.6328) are highlighted in Fig. 6. The -3 dB angular coverage is \(\pm 28^\circ\) and \(\pm 16^\circ\) for the simulated scenario and a 6-element hexagonal source antenna array alone, respectively. Moreover, the directivity is almost reduced by 6 dB, when compared with the source antenna array. The side-lobe level for the scenario is -7.5 dBi, with ripple level of 0.7 dB in the main beam. The quadratic phase distribution leads primarily to a reduction of directivity, and an increase in side-lobe level on either side of the main lobe. In general, the symmetry of the original pattern is maintained and ideal nulls in the pattern disappear. Thus, the minor lobes blend into each other and into the main beam, and they represent shoulders of the main beam instead of appearing as separate lobes. The broadband deflector facet with quadratic phase distribution increases the angular coverage (both the \(\theta\) and \(\phi\)-domain) at the expense of reduced directivity. The geometrical dimensions of the deflector configuration are larger than the source antenna array, and are primarily defined by the parameter \(h\).

The approach presented in this section can be applied for investigating different scenarios involving multiple deflector facets. Moreover, desired spill-over loss and gain requirements can also be formulated in objective function. The goal is to determine the phase distribution of multifaceted deflector configuration for different scenarios, e.g., achieving almost constant gain over the large angular coverage.

\[\text{Fig. 6: Quadratic phase distribution } \alpha(i_{\text{col/row}})\text{(degrees) [left]} \text{ vs directivity pattern (dBi) at 60 GHz for the } \phi = 90^\circ\text{ plane (red) and } \phi = 0^\circ\text{ plane (blue) [right]; 6-element source antenna array (solid) and a broadside deflector facet (dash)}\]

V. CONCLUSIONS

The extended MATLAB formulation for the parametric geometry of the deflector configuration has been validated with CST MWS simulations. A close agreement between the two gives confidence in MATLAB formulation to study the trade-offs in a passive electromagnetic deflector, using multi-objective genetic algorithm approach. The commercially available EM tools are too computationally intensive for the same. The real benefit of MATLAB formulation is the possibility of simulating any phase distribution function which can be approximated with a sum of polynomials, thereby enabling the investigation of different scenarios. Moreover, the use of multi-objective GA approach helps in studying trade-offs in a multifaceted deflector configuration. As a future work, the possibility of realizing phase shifters will be explored.

REFERENCES