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Focal Distance Reduction of Transmit-Array Antennas Using Multiple Feeds

Antonio Clemente, *Student Member, IEEE,* Laurent Dussopt, *Senior Member, IEEE,* Ronan Sauleau, *Senior Member, IEEE,* Patrick Potier, and Philippe Pouliguen

***Abstract*— The reduction of the focal distance of transmit-array antennas using multiple feeds is investigated theoretically and through full-wave simulations. A theoretical model of multiple-feed transmit-arrays is derived using analytic formulas; it shows that the focal distance can be divided by a factor of two using a quadruple-feed configuration. The theoretical results are validated through full-wave simulations for two transmit-arrays operating in the 60-GHz band.**

***Index Terms*— Transmit-array antenna, discrete lens, array lens, multi-feed antenna.**

I. Introduction

TRANSMIT-ARRAYS or discrete lens antennas [1] consist of a focal source illuminating a first antenna array operating in receive (*Rx*) mode and connected, using phase shift elements, to a second array operating in transmit (*Tx*) mode (Fig. 1).

A significant number of passive and active transmit-arrays have been demonstrated in the past with very attractive performance in terms of power efficiency, aperture efficiency, and bandwidth, especially at millimeter-wave frequencies [2]-[4]. These prototypes were designed with a single focal source usually implemented as 10–20 dBi standard-gain horn antennas with typical *F*/*D* ratios in the range of 0.5–1 (*F* is the focal distance and *D* the transmit-array diameter). This ratio is an important design parameter since it defines the total volume of the antenna and plays a key role for the integration and mounting of the antenna on the host platform (vehicle, building, aircraft, etc.). For instance, previous realizations in X-band required an *F/D* ratio of about 0.7 (21 cm) for a 23-dBi antenna gain [2] while integration on vehicles (train, bus, truck, car) would require a thickness not larger than 10 cm for SATCOM applications. Likewise, V-band transmit-arrays with *F* = 25 mm [3] were demonstrated and could be used for high data rate communications, but a low-profile solution (< 10 mm at least) is required for integration in laptop or other portable devices.

Multiple-feed transmit-arrays are investigated here for the first time as a solution to reduce the focal distance, thus leading to lower antenna profiles. This study is limited to a medium size array ($10\times\lambda_0$ in diameter) and dual or quadruple feeds; it is believed that a moderate number of feeds should be preferred in practical applications, as a large number of feeds would result in excessive complexity (feed network for amplitude/phase excitation of the focal feeds) for a minor benefit in terms of focal distance reduction. Moreover, we considered focal sources with $\cos^n\theta$ radiation patterns; such patterns are typical of standard gain horns or printed antenna arrays. The use of focal sources with optimized beam shapes is beyond the scope of this Letter.

An *ad-hoc* analytical model – previously implemented and validated experimentally for single-feed configurations [2],[3],[5] – is proposed in Section II for the simulation of multiple-feed systems. It is used in Section III to study numerically the performance of ideal transmit-arrays with single, dual or quadruple feeds in order to optimize the focal distance and source position in the focal plane and derive the bandwidth, efficiency and radiation patterns characteristics. These results are confirmed in Section IV through full-wave simulations of a linearly-polarized transmit-array in *V*-band. Conclusions are drawn in Section V.

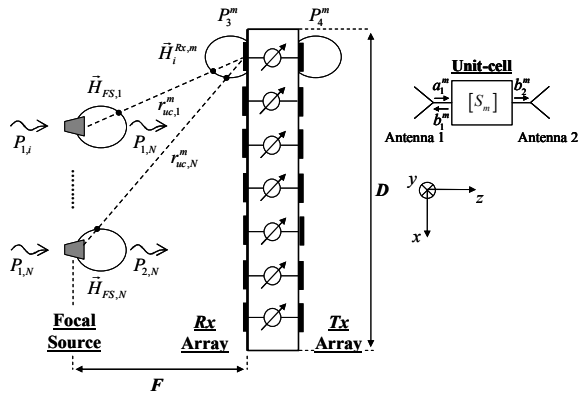


Fig. 1. Schematic view and power budget of a transmit-array with multiple feeds operating in transmit mode.

II. Analytical Model

A generic analytical model is proposed here to investigate the performance of multiple-feed transmit-arrays. The latter are composed of four parts in cascade (Fig. 1), namely (i) the focal source(s) (*FS*), (ii) the intermediate space between the focal source(s) and the *Rx* array, (iii) the unit-cells, and (iv) the free-space region. Ideal configurations with lossless and matched unit-cells are considered to identify the ultimate performance

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performance of such transmit-arrays.

A. Focal source and unit-cell

An ideal focal source with a $cos^n\theta$ radiation pattern is used here. Its directivity D_{FS} is given by

$$D_{FS}(\theta,\phi) = 2(n+1)cos^n\theta\,. \tag{1}$$

On the other hand, the unit-cell consists of a phase shifting section connected to *Rx* and *Tx* radiating elements (Fig. 1). Each element is modeled as a uniform aperture whose directivity is given by

$$D^{Rx/Tx,m}(\theta,\phi) = \frac{4\pi A_{phy}}{\lambda^2}cos\theta\,, \tag{2}$$

where A_{phy} is the physical area of the unit-cell, and m the index of the unit-cell on the antenna panel.

B. Power budget and radiation pattern of the transmit-array

Four power terms are defined to compute the power budget of the transmit-arrays studied here. P_1 is the total input power of the focal sources, P_2 the total power radiated by all focal sources, P_3 the incident power collected by the *Rx* array, and P_4 the power radiated by the *Tx* array. The antenna efficiency is defined as

$$\eta = P_4/P_1 = \eta_{FS}\cdot\eta_{SO}\cdot\eta_{IL}\,, \tag{3}$$

where $\eta_{FS} = P_2/P_1$ is the realized efficiency of the focal array, $\eta_{SO} = P_3/P_2$ is the spill-over efficiency, and $\eta_{IL} = P_4/P_3$ stands for the insertion loss of the unit-cells. According to the assumptions made at the beginning of this Section, we have $P_2 = P_1$, $P_4 = P_3$, and $\eta_{FS} = \eta_{IL} = 1$. Therefore, the incident power on unit-cell m is given by

$$P_3^m = \left|\sum_{i=1}^{N} a_{1,i}^m\right|^2, \tag{4a}$$

$$a_{1,i}^m = \sqrt{P_1}\frac{\lambda}{4\pi r_m^i}e^{-j\frac{2\pi r_m^i}{\lambda}}\vec{H}_{FS,i}\left(\theta_i^m,\phi_i^m\right)\cdot\vec{H}_m^{Rx,i}\left(\theta_m^i,\phi_m^i\right), \tag{4b}$$

where N is the total number of feeds, $a_{1,i}^m$ is the wave radiated by focal source i and incident on unit-cell m, $\left(r_i^m,\theta_i^m,\phi_i^m\right)$ are the spherical coordinates of unit-cell m with respect to the phase center of focal source i, $\left(r_m^i,\theta_m^i,\phi_m^i\right)$ are the spherical coordinates of focal source i with respect to unit-cell m, $\vec{H}_m^{Rx}$ and $\vec{H}_{FS,i}$ are the radiation patterns of unit-cell m and focal source i, respectively. They are deduced from the directivity curves given by Eqns. (1) and (2). The total power incident on the M-elements array is $P_3 = \sum_{m=1}^{M} P_3^m$.

The scattering matrix of the phase shifting element m is given by

$$S_m(\omega) = \begin{bmatrix} 0 & e^{-j\Delta\phi^m(\omega)} \\ e^{-j\Delta\phi^m(\omega)} & 0 \end{bmatrix}, \tag{5}$$

where $\Delta\phi^m(\omega)$ is the phase shift of unit-cell m, and ω is the angular frequency. Assuming that the mutual coupling between each *Tx* element is negligible, the total power transmitted by the array is $P_4 = \sum_{m=1}^{M} P_4^m = \sum_{m=1}^{M}\left|b_2^m\right|^2$ where the transmitted waves b_2 are expressed as

$$b_2^m = S_{21}^m(\omega)a_1^m\,. \tag{6}$$

If all the *Tx* elements have the same radiation pattern ($D^{Tx,m} = D^{Tx}\ \ \forall\ \ m$), the directivity $D_{TA}(\theta,\phi)$ and gain $G_{TA}(\theta,\phi)$ of the transmit-array can be calculated by

$$D_{TA}(\theta,\phi) = D^{Tx}(\theta,\phi)\frac{\left|\sum_{m=1}^{M} b_2^m e^{j\frac{2\pi}{\lambda}\sqrt{x_m^2+y_m^2}\sin\theta\cos\phi}\right|^2}{\sum_{m=1}^{M}\left|b_2^m\right|^2}, \tag{7a}$$

$$G_{TA}(\theta,\phi) = D_{TA}(\theta,\phi)\eta_{SO}\,, \tag{7b}$$

where (x_m,y_m) are the cartesian coordinates of unit-cell m.

The formulation derived above is used to determine the radiation performance of the transmit-arrays studied in Sections III and IV.

III. Ideal Transmit-Array with Perfect Phase Compensation

To demonstrate the benefits of multiple-feed configurations, we consider here a circular transmit-array ($D = 10\lambda_0$) with ideal phase compensation. The unit-cell size is $\lambda_0/2\times\lambda_0/2$. All focal sources are identical and $n = 4$ ($D_{FS} = 10$ dBi).

The study is carried out for three different configurations: single feed, dual feed, and quadruple feed (Fig. 2). In the single-feed case, the feed is centered with respect to the array axis. In the dual-feed case, two identical feeds are located on the x-axis at a distance d from each other. In the quadruple-feed case, the four identical feeds are distributed on a circle of diameter d.

The influence of the focal distance F and the source separation d on the theoretical gain of the dual- and quadruple-feed transmit-arrays are presented in Fig. 3. Three main regions are identified:

- For $d/D = 0$, the focal sources are co-located on the focal axis of the transmit-array; this case is equivalent to the single-feed configuration. A maximum gain of 28.6 dBi is obtained for $F/D = 0.43$.
- For $0 < d/D \le 0.1$ ($0 < d \le \lambda_0$), the optimal F/D ratio providing the maximum gain increases with d. Therefore, this configuration is not of interest since the volume of the transmit-array is larger than the single-feed configuration. A maximum gain of 28.6/28.9 dBi is obtained for $F/D = 0.46/0.79$ and $d/D = 0.02/0.09$ for the dual-/quadruple-feed configuration, respectively.
- For $d/D > 0.1$ ($d > \lambda_0$), a local maximum gain value of 28.5/28.7 dBi is obtained for $d/D = 0.42/0.52$ and $F/D = 0.34/0.25$ for the dual-/quadruple-feed configurations, respectively.

The theoretical directivity and gain of the three configurations are represented in Fig. 4 as a function of F/D. The main radiation characteristics, including the side-lobe level (SLL) and power budget of the three antenna configurations are provided in Table I. These results show that the use of a quadruple-feed system allows reducing the focal distance by a factor close to two (from $F/D = 0.43$ to $F/D = 0.25$) as compared to a single-feed configuration, while maintaining very similar performance in radiation. By comparing the 1- and 4-feeds cases in Table I, we can predict a general trend, namely an increase of the SLL with the number of feeds. This is due to a more uniform illumination of the array by the source(s) (reduced edge illumination, as for reflector antennas).

Although not reported here in details, simulations have shown that multiple feeds configurations do not degrade the beam-steering capabilities of the transmit-array.

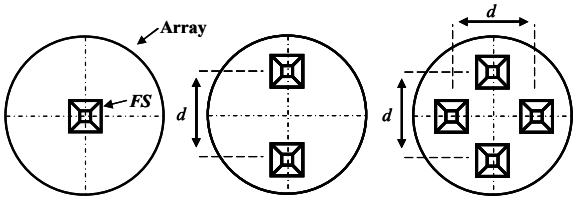


Fig. 2. Single-, dual-, and quadruple-feed configurations.

The normalized maximum gains of the single-, dual-, and quadruple-feed transmit-arrays are plotted in Fig. 5 as a function of frequency. The 3-dB gain-bandwidth product of the antenna increases with the number of feeds from 40% for a single feed to 46% for a double feed and 65% for a quadruple feed. In these computed frequency responses, the phase shift of each unit-cell was optimized at the nominal central frequency f_0 and kept constant with frequency. As the unit-cell is ideal, the bandwidth limitation is only due to the differential spatial phase delays between the focal source(s) and the unit-cells: in the single-feed case, the distance between the source and the center edge cell is $6.4\lambda_0$ and results in a phase error of 75.6° for a 10% frequency shift, whereas in the 4-feeds case, these values are reduced to $3.3\lambda_0$ and 28.8°, respectively. In a real case, the transmit-array bandwidth would be limited by the bandwidth of the unit-cell which is typically lower than 40% for printed technologies.

IV. Linearly-Polarized Transmit-Array in *V*-Band

In order to validate the theoretical model and results presented above, the performance of a single- and a quadruple-feed linearly-polarized square transmit-array have been investigated in *V*-band. In this section, the results obtained using this model have been compared to full-wave simulations carried out using the Ansys HFSS Hybrid Finite Element-Integral Equation Method (FE-BI) solver.

The two transmit-arrays are based on the unit-cells proposed in [3] with a 180° (1-bit) phase quantization. Each array includes 20×20 elements, and their total size equals $10\lambda_0 \times 10\lambda_0$. One or four 10-dBi standard gain horns are used as focal sources. The phase distributions (Fig. 6), focal distance and feed separation have been optimized using the theoretical model described in Section II. The optimal F/D ratios are 0.54 and 0.34 for the single- and quadruple-feed cases, respectively. In the quadruple-feed configuration, the optimal feed separation is $d = 0.54D$.

From a practical point-of-view, this focal distance reduction from 27 mm ($F/D = 0.54$) to 17 mm ($F/D = 0.34$) significantly improves the feasibility of the integration of such structures in smart devices such as laptops, TV or multimedia appliances.

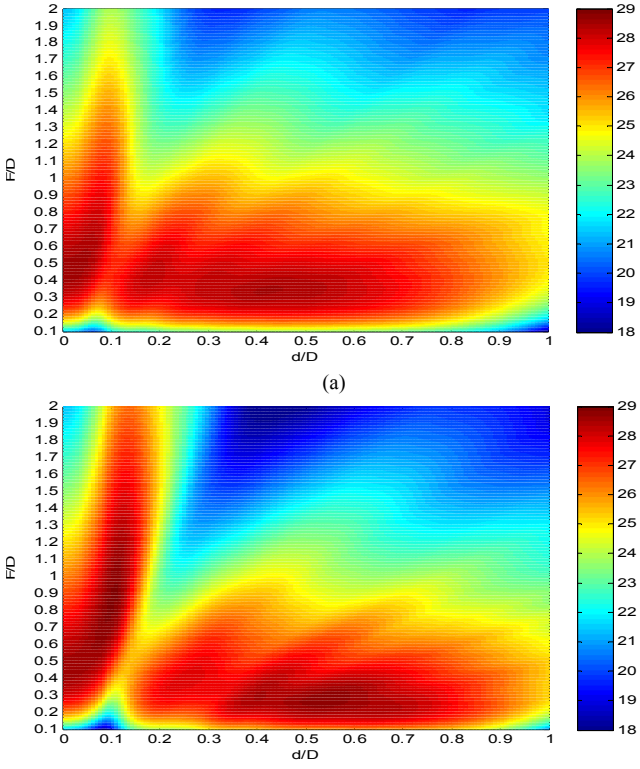


Fig. 3. Simulated gain (color scale in dBi) as a function of the F/D ratio and feed separation d (normalized to D) for (a) dual-, and (b) quadruple-feed configurations. $D = 10\lambda_0$.

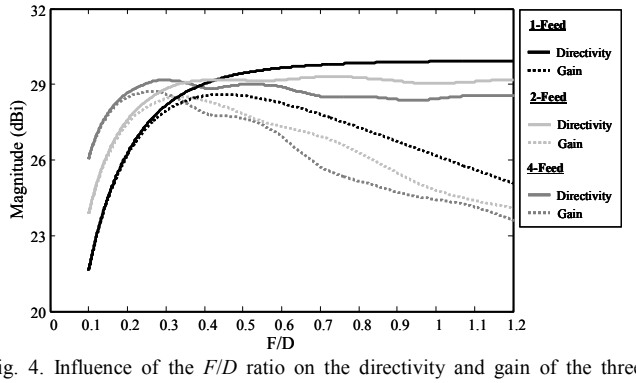


Fig. 4. Influence of the F/D ratio on the directivity and gain of the three configurations with $d/D = 0.42$ and 0.52 for dual- and quadruple-feed configurations, respectively. $D = 10\lambda_0$. The fast gain drop beyond $F/D \sim 0.5$ is due to spill over loss [3].

The theoretical and simulated gain-frequency responses of these two transmit-arrays show a good agreement as demonstrated in Fig. 7. A frequency shift of about 2 GHz (3%)

and a slightly larger bandwidth (model: 17.5/15.8 GHz, HFSS simulations: 19.5/17.8 GHz, for the single/quadruple-feed) can be observed. This small discrepancy is likely due to convergence issues of the simulations which need very large memory resources (> 90 Go). The gain of the single-feed configuration measured in the 50–70 GHz band shows a good agreement with the theoretical model, confirming the hypothesis of incomplete convergence of the full-wave simulation.

TABLE I

THEORETICAL PERFORMANCE OF TRANSMIT-ARRAYS OPTIMIZED FOR MAXIMUM GAIN FOR A SINGLE, DUAL AND QUADRUPLE FEED.

	1 feed	2 feeds	4 feeds
Focal source gain (dBi)	10	10	10
Optimum *F*/*D* ratio	0.43	0.34	0.25
Directivity (dBi)	29.2	29.0	29.1
Gain (dBi)	28.6	28.5	28.7
SLL (dB)	29.2	15.3	24.5
Spill-over loss (dB)	0.54	0.5	0.27
Aperture efficiency (%)	73.5	71.6	74.9
Total efficiency (%)	88.1	88.6	92.7
Bandwidth (%)	40	46	65

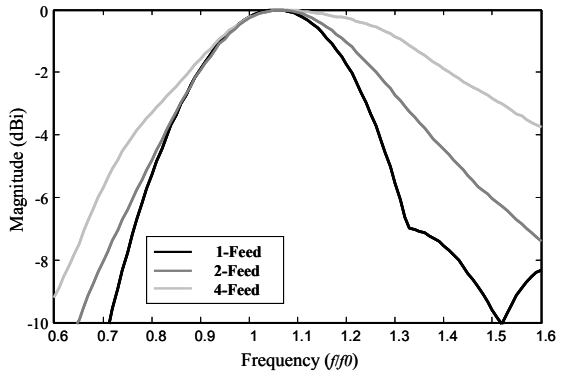
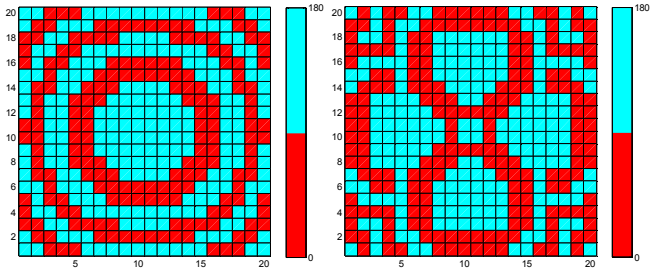


Fig. 5. Simulated normalized gain-frequency responses of the single-, dual-, and quadruple-feed configurations.



(a) (b)

Fig. 6. Phase distribution (deg.) on the transmit-array aperture for the (a) single- and (b) quadruple-feed configurations.

The theoretical and simulated broadside gains of the quadruple-feed configuration have been computed at 60 and 62 GHz to take into account the frequency shift mentioned above; they are in very good agreement (Fig. 8).

V. CONCLUSION

The feasibility of focal distance reduction for transmit-array antennas using multiple feeds has been investigated theoretically and validated through full-wave simulations. It is shown that a quadruple-feed system allows reducing the focal length by about a factor of two with similar radiation performances as the single-feed transmit-array.

These results offer the perspective to design lower profile transmit-array antenna systems, thus enabling an easier integration onto vehicles, building or other platforms, with a limited increased complexity.

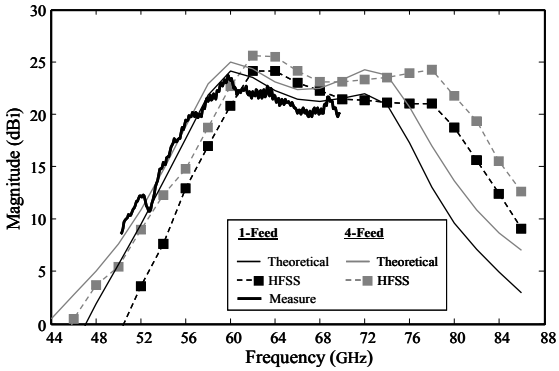


Fig. 7. Theoretical (analytical model) and simulated (full-wave) gain-frequency response for the single- and quadruple-feed transmit-arrays in *V*-band. Measured results of the single-feed configuration available in [3].

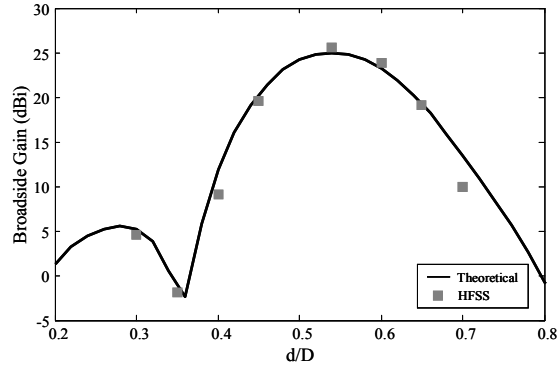


Fig. 8. Theoretical (60 GHz) and simulated (62 GHz) broadside gain as a function of the feed separation for the quadruple-feed transmit-array in *V*-band.

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