CALCULATING FAR-FIELD PATTERNS OF LARGE ARRAYS COMPOSED OF SEQUENTIALLY ROTATED ELEMENTS : A FIRST ANALYSIS USING FDTD

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***Abstract* – This paper provides a first insight into the analysis of large phased arrays using an FDTD based field solver. A feature of the arrays considered here is the use of sequentially rotated elements, which requires special design measures. Therefore, the calculation of the far fields of the array based on FDTD-simulations is described in great detail, and different models for coupling are introduced.**

1 INTRODUCTION

Several antenna concepts on phased arrays are being investigated within the **SANTANA** project (**S**mart **Ant**enna Termi**na**l) [1], funded by the German government (BMBF) on behalf of the DLR. The goal of this project is the realisation of a first prototype of such an antenna. Possible applications are terminals for airborne broadband satellite communications. One promising concept is an array at 30 GHz, which uses the sequential rotation principle for achieving a better circular polarisation. The requirements of this antenna are very stringent, as the axial ratio demands have to be fulfilled for a scan range of as much as ±60°, and still satisfy ETSI specifications [2]. Because it is a planar array, the constraints on the axial ratio are very demanding, and the design is therefore composed of patch elements, each of them circularly polarised, arranged in a sequentially rotated fashion. The number of elements can amount to more than 4,000. The beam of the array can be steered and formed electronically by applying different amplitudes and phases to the antenna elements by employing the Digital Beam Forming (DBF) technique. Due to the special arrangement of the patch elements, the coupling effects have a large impact on the axial ratio and thus on the array pattern, and are therefore of main interest for the design.

This paper focuses on how to approximate the far field of the complete array using an FDTD (Finite Difference Time Domain) based field solver. The aim is to derive the correct far-field from the results of the simulations without having to model the whole array. Therefore, models have been defined for describing the coupling effects using only a limited number elements.

First, the general configuration of the array is explained. Thereafter, the FDTD-modelling is presented in detail, along with the problems encountered when calculating the far fields. Then, the applied coupling models, that are the basis for the determination of the far field of the complete array are introduced and discussed.

2 GENERAL CONFIGURATION

The basic antenna element consists of a circularly polarised patch element, fed by a circular waveguide via an elliptical slot. All patches of the array have a truncated square shape, and can be separately steered in amplitude and phase. The schematic of a single patch element is displayed in figure 1.

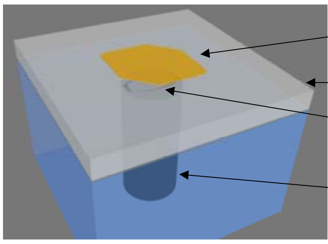

Figure 1: Layout of the basic element.

As mentioned previously, these elements will be sequentially rotated as indicated in figure 2, in order to improve the axial ratio. The patches are not only rotated spatially 90° with respect to each other, but also fed with a 90° phase shift. Normally, the sequential rotation principle is used to generate circular polarisation from linearly polarised patch elements [3]. Yet, the use of sequentially rotated circularly polarised elements enhances the polarisation behaviour of the array [4], and suppresses the generation of grating lobes, thus taking the design one step further towards fulfilling the stringent requirements.

The array will be composed of approximately 4,000 elements, arranged in subgroups of 4 rotated patches.

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The frequency bandwidth is 29.5-30 GHz, and the element spacing is approximately 5 mm (about half a wavelength at 29.7 GHz). The maximum scan angle is 60° with respect to boresight. Because the bandwidth is an uncritical parameter in the design, all radiation patterns given in this paper will be determined for 29.7 GHz, the centre frequency of the band.

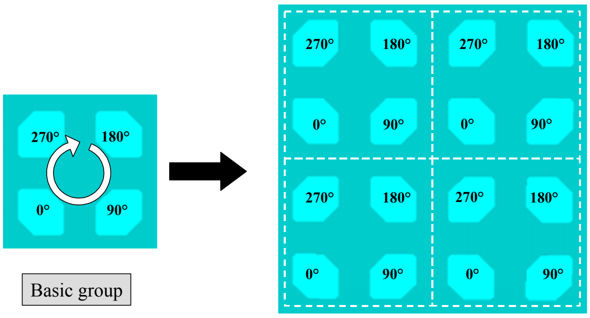


Figure 2: Patches arranged according to the sequential rotation principle.

3 FAR FIELD CALCULATIONS

The radiation patterns and the input return loss are derived with the help of the FDTD-field solver EMPIRE. It is impossible to model a large number of such complex elements due to practical restrictions as available memory and computation time. This applies especially to cases like this, where the FDTD-grid has to be very fine due to the shape of the elliptical feeding slot. First simulations of the patch with different degrees of discretisation showed remarkable differences regarding the return losses. So, a fine meshing is compulsory for this patch configuration. Moreover, beam steering, which is one of the key points of the design, is difficult to implement with FDTD-modelling. Thus, the following approach has been adopted: only a small number of elements are modelled, yet the most significant coupling effects, also called "first order" coupling effects, are included. Normally, this involves embedding the active element in the array structure, and taking only its direct neighbours into account, as shown in figure 3.

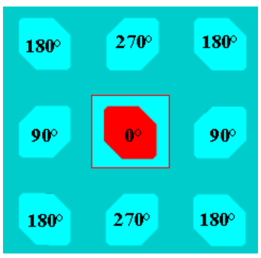


Figure 3: Basic coupling model (active patch = red).

These neighbouring patches are considered as passive components, and are terminated with an ideal impedance (in the model, a PML-wall). The far fields of these sub-modules are multiplied by the appropriate array factor, in order to obtain the far field patterns of the array. By adding a phase shift for each element, the influence of coupling on the scan performance can also easily be investigated. Because the individual far fields are superimposed, it is of great importance to approximate these patterns as accurately as possible, in order to avoid errors in the resulting array characteristics.

4 FDTD MODELLING

The FDTD modelling applied here is standard: the complete radiating structure (active and passive patches) is enclosed by a box (denoted FF-box here) that registers the near fields, as shown in figure 4. The FF-box has always to be completely closed, either by enclosing the whole radiating structure, or by closing the box via an infinite ground plane as depicted in figure 4.

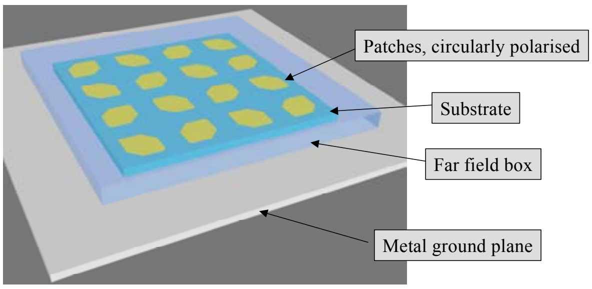


Figure 4: Definition of the FF-box.

In order to obtain the far fields, the E- and H-fields on the walls of this box have to be transformed into the far field. Two problems are encountered here. The first one is the effect of the infinite ground plane, which acts like a mirror. This can be solved by simply applying the image theory [5]. The second arises from the fact that the FF-box has to cut the substrate in order to reach the ground plane, thus violating the equivalence theory [5]. Although this is a typical problem when modelling planar structures using FDTD, practical solutions are rarely found in literature. As the substrate is relatively thick with respect to the wavelength, the error in the far fields is mainly caused by the surface waves propagating through the side walls of the FF-box that cut the substrate. These fields are misinterpreted during the far field transformation. The only solution is to use a finite size substrate. Yet, this on its turn introduces errors in the far field, due to the radiation and reflections at the edges of the substrate.

To solve these problems two general FDTD-models have been defined, and their far fields will be compared:

- A model using a finite size substrate of 20 mm x 20 mm, with an FF-box completely enclosing the substrate (not cutting it).
- A model with an infinitely large substrate, yet with the same FF-box (size and position) as used in the previous model. Here, the FF-box cuts the substrate.

The return loss and far fields for the cardinal (azimuth: 0° and 90°) and inter-cardinal planes (azimuth: 45°) have been compared for three different patch configurations, in order to study the differences between the two models. These configurations are representative of the coupling models presented in the next section. For all configurations, the same patch is always excited (see table 1, red=active). The results are listed in table 1, where the maximal differences between the far fields derived from the models with finite and infinite substrate are indicated, for an elevation range of -90° to +90°. It is clearly visible that, for all configurations, the differences between the two models are relatively small. This is also illustrated in figure 4 where the far field patterns for the 4x4 model for both cases are displayed.

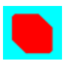
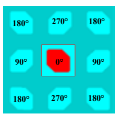
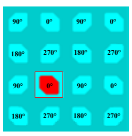
Patch Configurations	Maximum differences in far field gain finite - infinite substrates
	Theta: 0.8 dB Phi: 0 dB
	Theta: 1.2 dB Phi: 0 dB
	Theta: 1.2 dB Phi: 0.1 dB

Table 1: Comparison between finite and infinite substrate models.

The phases obtained with both models have also been compared. They show even smaller discrepancies. One of the main causes for this is the fact that the larger part of the radiated energy is not propagating via surface waves as expected in the first place. Other simulations, using vias to eliminate any possible surface waves support also this hypothesis.

Therefore, it can be stated that the fact that the FF-box intersects with the substrate does not significantly diminish the accuracy of the far field patterns, even when multiple elements are involved. Yet, this cannot be generalised, and should be checked for each case separately.

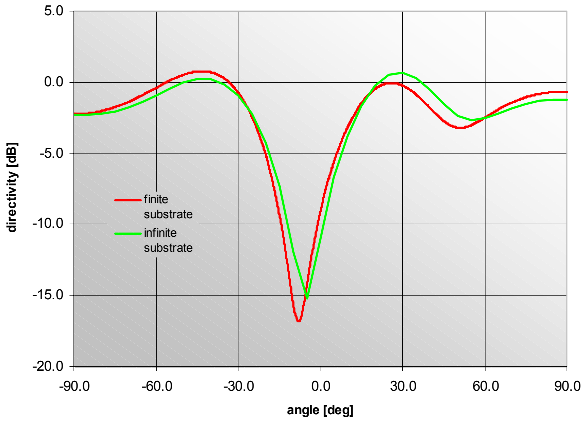


Figure 4: Far field patterns (theta component) of a 4x4 patch model with finite and infinite substrate.

5 COUPLING MODELS

Different coupling possibilities have been compared [6] for the sequentially rotated patches: a single patch, a patch surrounded by neighbouring elements as shown in figure 3 (first order model), and a group of 4 patches surrounded by neighbouring elements as depicted in figure 5 (4x4 model). Extensive investigations show that latter model is the most suitable for modelling the coupling effects with the available resources (CPU speed/memory requirements). The differences between the far fields obtained using the first order model in figure 3 and the 4x4 model are rather large, which can be explained by the spatially configuration of the sequentially rotated patches.

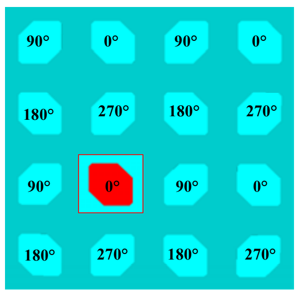


Figure 5: Coupling model applied

The 4x4 model above then is used to determine the far fields of the complete array. For the azimuth=0°, the far field patterns for scan angles of 0° and 60° are depicted in figure 6. The pattern at a scan angle of 60° shows an unexpected sidelobe for an elevation of –10°, which is due to the coupling between the patches. Calculations using the far field pattern of only a single patch did not show such sidelobes.

4 CONCLUSIONS

An FDTD-model for determining the far field characteristics of large arrays has been presented. The key issue discussed here is how to determine reliable far field patterns of sub groups, in order to avoid computational errors in the far field characteristics of large arrays. It has been shown that a model with a finite size substrate can be used that does not violate the laws of physic. For sequentially rotated patch elements the coupling effects can best be described by a 4x4 element model that can efficiently be used for determining the far field patterns at various scan angles of the array. The effect of surface waves plays only a minor role in the design despite the thickness of the substrate.

REFERENCES

[1] Dreher, A., S. Holzwarth, C. Hunscher, A. Jacob, and N. Niklasch, " Smart antenna terminal for broadband aeronautical applications", Fifth European workshop on mobile/Personal Satcoms Proceddings (EMPS 2002), September 25-26, Baveno (Italy), 2002, pp. 263-269.

[2] ETSI EN 301 459, Satellite Earth Stations and Systems (SES), section: Harmonised EN for Satellite Interactive Terminals (SIT) and Satellite User Terminals (SUT) transmitting towards satellites in the geostationary orbit in the 29.5 to 30.0 GHz frequency bands covering essential requirements under article 3.2 of the R&TTE Directive, V1.2.1, October 2000.

[3] Teshirogi, et al., "Wideband circularly polarised array antenna with sequential rotations and phase shift of elements", International Symposium on Antennas & Propagation Proceedings, Japan, 1995, pp. 117-120.

[4] Nauwelaers, B., G. Raguenet, and A van de Capelle, "La rotation sequentielle et la polarisation circulaire", Conference Journees Internationales de Nice sur les antennas, November 13-15, 1990, pp.459-462.

[5] Harrington, R.F., Time-Harmonic Electromagnetic fields, pp. 103-111, McGraw-Hill Book company, New York, 1961.

[6] Su, T. and H. Ling, "On modelling mutual coupling in antenna arrays using the coupling matrix", Microwave and Optical Technology Letters, Vol. 28, No. 4, February 2001, pp. 231-237.

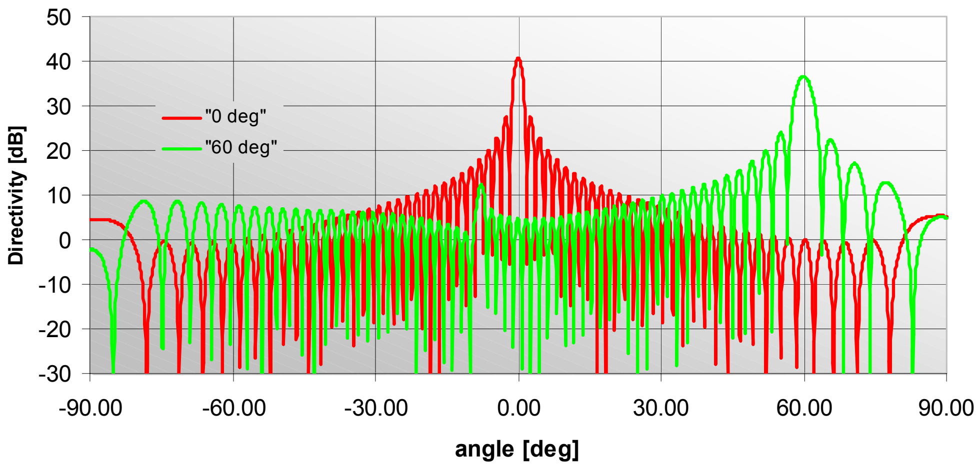


Figure 6: Far field patterns of the array