Phased Antenna Array Cross-Polarization Tuning

Einstellung der Kreuzpolarisation von Gruppenantennen

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Abstract — The polarization purity is a key parameter of the antennas used for satellite communications. To obtain a sufficient polarization purity for a complex antenna system, especially for planar antennas, a specific tuning procedure must be performed. For this purpose, a brief description of the polarization states is presented, clarifying the subject of the polarization matching. A verified algorithm for tuning of polarization of phased antenna array is also presented and further developed to investigate the possibility to obtain a broadband polarization characteristic. Experimental results are presented and discussed.

Zusammenfassung — Die Polarisationsreinheit ist ein Schlüsselparameter bei Antennen in der Satellitenkommunikation. Um auch in komplexen Antennensystemen, wie beispielsweise in planaren Antennenanordnungen, eine ausreichende Polarisationsreinheit sicherzustellen, muss die Antenne in dieser Hinsicht speziell abgestimmt werden. Zu diesem Zweck wird eine kurze Beschreibung der Polarisationszustände gegeben, um die Problematik der Polarisationsanpassung zu verdeutlichen. Ein verifizierter Algorithmus zur Einstellung der Polarisation eines phasengesteuerten Antennenarrays wird ebenfalls vorgestellt und hinsichtlich einer breitbandigen Einstellung der Polarisationscharakteristik weiterentwickelt und untersucht. Abschließend werden experimentelle Ergebnisse dargelegt und diskutiert.

I. Introduction

The polarization purity plays a key role for optimal channel densification of the existing geostationary-satellite orbit (GSO) and especially of the emerging non-geostationary-satellite orbit (NGSO) constellations [1], [2]. The need for at least two active broadband connections at time – one with the rising satellite and one with the setting over the horizon – each of them usually with different polarizations, raises questions about the cross-polarization discrimination (XPD) tuning of electronically steerable phased antenna arrays (PAA), capable to provide multiple active beams at a time.

The goal of the current work is to propose a method for XPD optimization in a frequency band and to present results, obtained by different criterion for compensation.

The polarization purity can be influenced by any structure in the antenna's aperture proximity – e.g. supporting elements, housing or radome.

A complete characterization of an antenna polarization properties requires its full complex 2D pattern, represented with pattern matrix of the form:

$$F(\theta,\varphi) = \begin{bmatrix} f_{HH}\, f_{VH} \\ f_{HV}\, f_{VV} \end{bmatrix}$$

This matrix form is convenient for explanation of electromagnetic wave interaction with other structures during the wave propagation – i.e. for simulation of radar systems, but is inappropriate for common antenna systems characterization.

All possible polarization states of an electromagnetic (EM) system can be represented as a point on the Poincare sphere – Fig. 1, where the linear polarizations are located on its "equator", the circular polarizations – on the sphere poles, and the elliptical polarizations – anywhere between them. The right-hand polarizations (elliptical and circular) are placed on the bottom/south hemisphere, the left-hand polarizations – on the north one. An important property of the Poincare sphere is that polarization states placed on opposite points on the sphere surface are orthogonal to each other, hence to every polarization state corresponds a single orthogonal phase state.

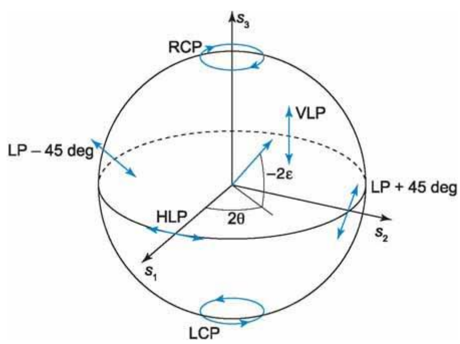

Fig. 1. The Poincare Sphere

In the praxis it is common to decompose the electric field vector on the major X and Y axis of a Cartesian coordinate system, known as the "third Ludwig definition" [4]:

$$E_{h,co} = E_\theta \cos\varphi - E_\varphi \sin\varphi \qquad (1)$$

$$E_{v,xo} = E_\theta \cos\varphi + E_\varphi \sin\varphi \qquad (2)$$

In the case of circular polarization, a polarization state can be described as a sum of two – left and right – waves with components [5]:

$$E_{lhcp} = \frac{E_\theta - jE_\varphi}{\sqrt{2}} \qquad (3)$$

$$E_{rhcp} = \frac{E_\theta + jE_\varphi}{\sqrt{2}} \qquad (4)$$

II. Polarization Control

In this section we will analyze the polarization control on a PAA, based on the magnitude of two orthogonal excitation waves. In the following analysis we will use the electric fields

E_V and E_H, which correspond to the antenna vertical and horizontal axes. We will consider the electric field, projected on a x-y plane, perpendicular to the beam direction z, as shown in Fig. 2. The goal of the amplitude control is to identify the appropriate attenuation factors for the excitation fields E_V and E_H, according to the required specification for the polarization in the xy plane.

For the ideal case – without aperture feed error and no radome depolarization – the fields E_V and E_H depend solely on the beam azimuth and tilt in respect to the boresight of the antenna.

The unit vectors $\hat{h}$ and $\hat{v}$ are specified by the antenna geometry. We select the unit vectors $\hat{x}$ and $\hat{y}$ of the projection plane such that for an elevation of 0° and for an azimuth of 0° the vector pairs $\hat{x}$ and $\hat{h}$, and $\hat{y}$ and $\hat{v}$ are collinear. The projection plane for a beam with a different azimuth and elevation is obtained by adjusting the appropriate angles and without any roll along the beam axis z.

We consider a transmitting antenna with a beam with an elevation θ and azimuth φ. We can compute the projection of the antenna excitation fields E_H and E_V on the E_X and E_Y components of this beam using the following equations, which have been derived from the geometry of the problem, as shown in Fig. 2:

$$E_{VX} = E_V \sin\varphi \quad (5)$$

$$E_{VY} = E_V \sin\varphi \cos\theta \quad (6)$$

$$E_{HX} = E_H \cos\varphi \quad (7)$$

$$E_{HY} = -E_H \sin\varphi \cos\theta \quad (8)$$

From the sum of the coaxial projections – E_{VX} and E_{HX} – and E_{HY} and E_{VY} – the effective magnitude of the resulting vectors in the xy-plane can be derived:

$$E_X = \sqrt{(E_V \sin\varphi)^2 + (E_V \sin\varphi \cos\theta)^2} \quad (9)$$

$$E_Y = \sqrt{(E_H \cos\varphi)^2 + (E_H \sin\varphi \cos\theta)^2} \quad (10)$$

From the difference between E_X and E_Y one can calculate the amplitude correction for each excitation field E_V and E_H, as shown on Fig. 4.

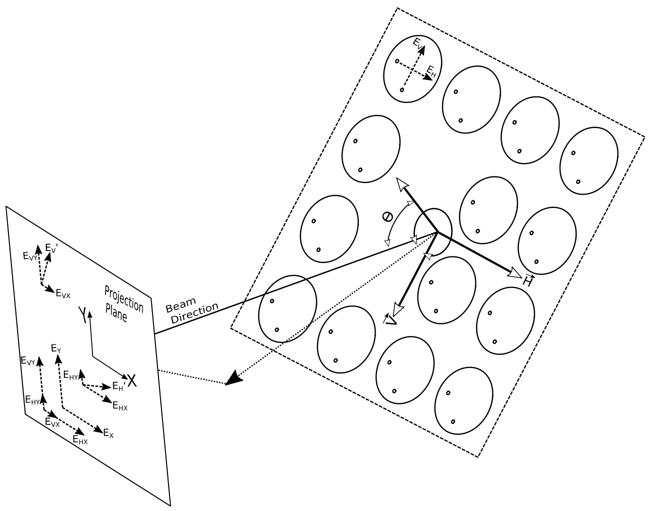

Fig. 2. Field components projection visualization

III. CW-Tuning Constraints

The corrections, obtained as described in the previous section, can be used as a theoretical basis for further optimization of the antenna's XPD, as they do account solely the geometrical orientation of the beam in the space.

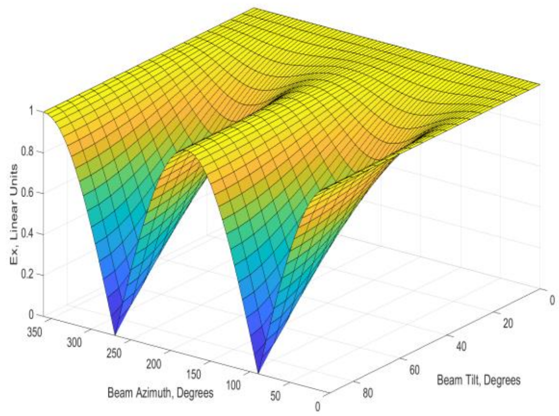

Fig. 3. E_X values as a function of beam position

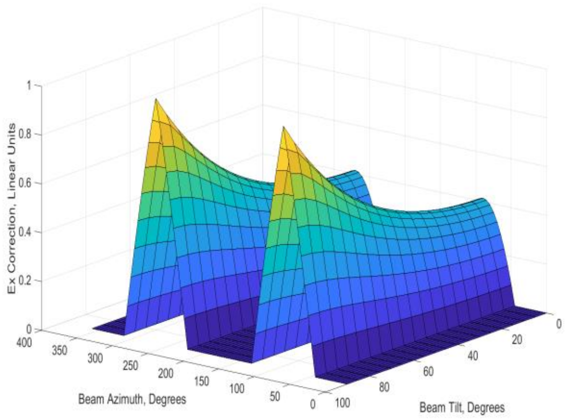

Fig. 4. E_X-corrections as a function of beam position

Different measurement and correction approaches for E_V and E_H component level and phase difference can be applied, depending on the available test facility and equipment. Because the estimations are based on the vector magnitude ratios, it is hard (or even impossible) to predict the XPD tuning behavior for more than a single CW frequency or an extremely narrow bandwidth.

IV. XPD Tuning procedure

As shown in the previous sections, the cross-polarization discrimination at the elements of a PAA depends on the beam direction. We can optimize the XPD by introducing phase and amplitude corrections for the E_V and E_H excitation fields. The corrections can be calculated for single frequency points, but it is not straightforward to estimate the broadband XPD characteristics of the antenna under those corrections. We propose an experimental setup which provides a set of correction coefficients, each of them with a specific frequency behavior.

The presented tuning procedure is split in two stages – identification of possible correction combinations and measuring each one over a broad frequency band.

The first stage itself is split in two substages – one for the identification of possible phase corrections, and one for the attenuation corrections. Considering the stronger effect of the phase deviation from the aimed 90° between the X- and Y- field components, the phase tuning is performed before the amplitude one.

The procedure for calculating the phase corrections is based on selecting a proper initial value, which is derived for short list of frequencies, and then measuring the antenna performance with this correction over a larger band.

In this works we consider three basic methods for selecting the phase and amplitude corrections:

- C-approach, delivering the correction providing a maximal XPD for the central operation frequency
- B-approach, delivering the correction for further optimization of the maximal XPD over the short list frequencies.
- W-approach, delivering the correction for optimization of the minimal XPD over the short list of frequencies.

The output of this stage can be represented as shown in Table I, where each row and column contains a correction obtained by a different approach. Depending on the PAA behavior different approaches could lead to the same result, reducing the count of unique correction combinations.

TABLE I. CORRECTION COMBINATIONS

Phase \ Att	Ca	Ba	Wa
Cp	Ca-Cp	Ba-Cp	Wa-Cp
Bp	Ca-Bp	Ba-Bp	Wa-Bp
Wp	Ca-Wp	Ba-Wp	Wa-Wp

The corrections marked with an “a” subscript correspond to the obtained attenuation corrections, ant those with a “p” subscript - to the phase one.

A. Tuning Setup

The tuning setup consists of RF source, RF switch and two reference antennas for RHCP and LHCP- Fig. (5). The distance between the reference horns and the AUT meets the far-field criterion. Figure 5 depicts the corresponding phase shifting and level correction circuits on the feed lines for two patch elements of a PAA.

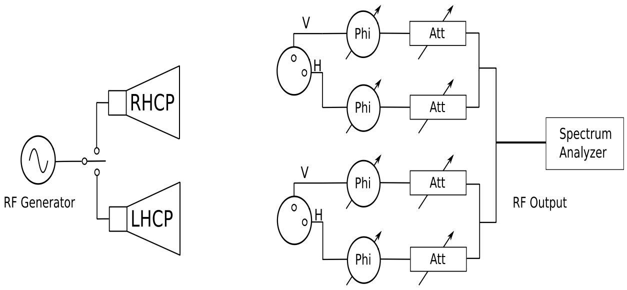

Fig. 5. XPD tuning setup

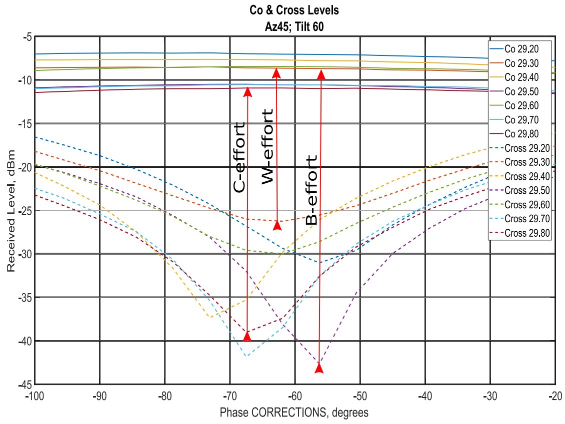

Fig. 6. Phase tuning. Measurement data. Raw Data.

B. Tuning Procedure

1) Phase Tuning

The phase tuning is performed by adding a phase shift for one of the linear components – **V** or **H** – and measuring the Co- and Cross-level for different frequencies on the receiver side. A typical obtained curve is displayed on Fig. 6 – for clarification of the process the range of phase corrections is wider than needed for the actual tuning procedure.

Graphically the analysis of the obtained power series can be described as choosing the points on the XPD surface, around which the further amplitude optimization will be performed.

Depending on the behaviour of the PAA, some of the correction values for different approaches can be equal.

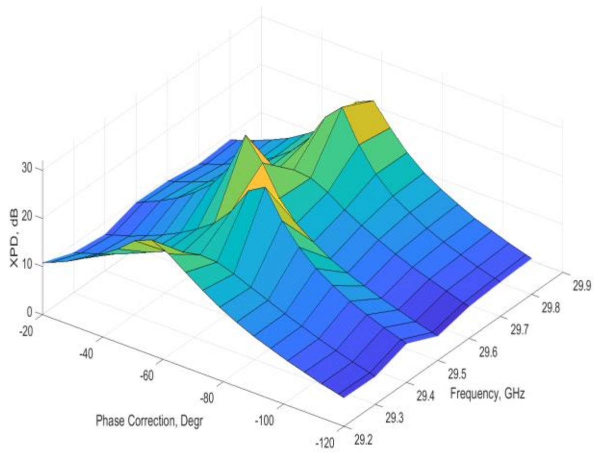

Fig. 7. Phase tuning. Measurement data. Surface representation

2) Amplitude Tuning

The amplitude tuning procedure resembles to the phase one with loading different gain corrections for the V- or H channel for particular phase correction.

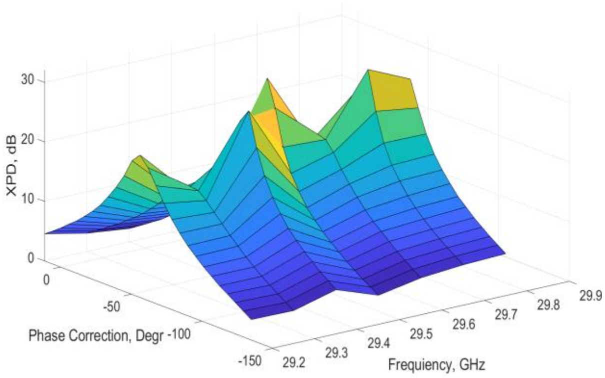

Fig. 8. Phase Optimization

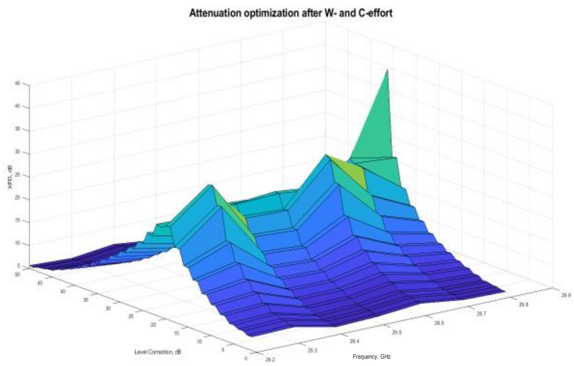

Fig. 9. Attenuation Optimization after Bp-effort

The complete procedure can be undertaken multiple times consequently in order to achieve better results. The optimization points defined by a particular optimization step will be used as initial point for the next one – i. e. the phase corrections, defined by the first optimization step, will be held constant during the obtaining the level correction coefficients.

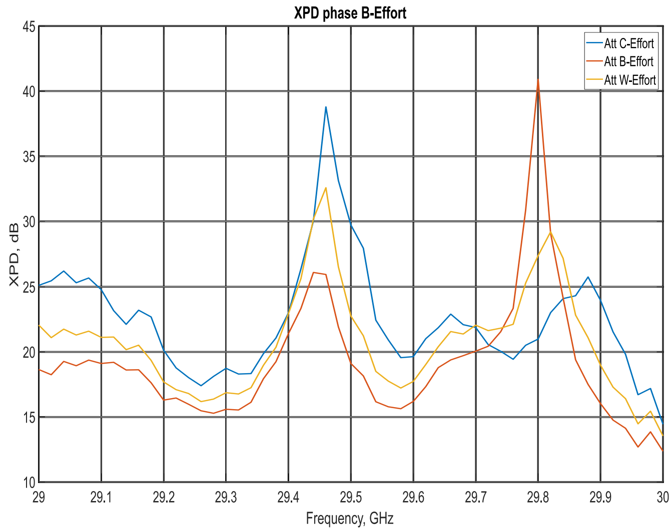

Fig. 10. Attenuation Optimization after phase Wp- and Cp-effort

V. Data analysis and conclusions

For all combinations of phase and level corrections for a particular beam pointing direction, the XPD of the antenna was measured in the wide frequency band. The results for three of them are presented on Fig. 10.

Expectedly all submitted correction combinations provide an increase of the initial XPD.

All results were analyzed and sorted according the XPD behavior in the measured frequency band – minimal achieved XPD, lowest variances in the frequency band and the maximal achieved XPD. The obtained corrections values can be stored and applied according to the current connection requirements.

The optimal approach seems to be a sequential optimization with the W-effort – which leads to limitation of cross-polarization interferences in the band with lowest ripples in the XPD across it.

The B-Effort leads to extremely high XPD values for particular frequency, but on the cost of overall lowest XPD in the band.

References

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