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Research Article

Accurate Modeling and Analysis of Isolation Performance in Multiport Amplifiers

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A Multiport Amplifier (MPA) is an implementation of the satellite power amplification section that allows sharing the payload RF power among several beams/ports and guarantees a highly efficient exploitation of the available DC satellite power. This feature is of paramount importance in multiple beam satellite systems where the use of MPAs allows reconfiguring the RF output power among the different service beams in order to handle unexpected traffic unbalances and traffic variations over time. This paper presents Monte Carlo simulations carried out by means of an ESA in-house simulator developed in Matlab environment. The objective of the simulations is to analyse how the MPA performance, in particular in terms of isolation at the MPA output ports, is affected by the amplitude and phase tracking errors of the high power amplifiers within the MPA.

1. Introduction

Satellite telecommunication payloads are required to guarantee an increasing flexibility/reconfigurability in order to optimize their performance for different operational conditions, which may arise during the satellite lifetime. This flexibility requirement is mainly due to the large variety of services to be provided and to the uncertainties of the traffic requests that such services may have during mission lifetime. In particular, one of the main payload's design objectives is to effectively combine coverage, power, and bandwidth flexibility, while minimizing the overall DC power consumption and mass, at attractive costs for operators. Among the abovementioned, in the case of multiple beam satellite systems, one of the most important payload flexibility means is the capability of reconfiguring RF output power among the different service beams in order to handle unexpected traffic unbalances and traffic variations over time. In this respect, at payload RF-front-end level, several implementations can be considered, depending on the type of integration among the power amplification section and the beam forming section. In particular, considering self-standing power sections, the solution that guarantees the highest level of RF power flexibility is that based on Multiport Amplifiers (MPAs) [1]. Generally speaking, a Multiport Amplifier is an implementation of the power amplification section that allows sharing the payload RF power among several beams/ports and guarantees a highly efficient exploitation of the available DC satellite power [2].

This paper presents Monte Carlo simulations carried out by means of an ESA in-house simulator developed in Matlab environment. The objective of the simulations is to analyse how the MPA performance, in particular in terms of isolation at the MPA output ports, is affected by the amplitude and phase tracking errors of the high power amplifiers within the MPA.

2. Multiport Amplifier (MPA)

A Multiport Amplifier relies on the parallel amplification of the signals by a stack of power amplifiers, which guarantees the power sharing among the output ports. A plurality of input signals is transformed by the input multiport network (INET) and presented to the stack of amplifiers (HPAs), usually Traveling-Wave Tube Amplifiers (TWTAs). Once amplified, the signals are then recombined by the output multiport network (ONET) [1].

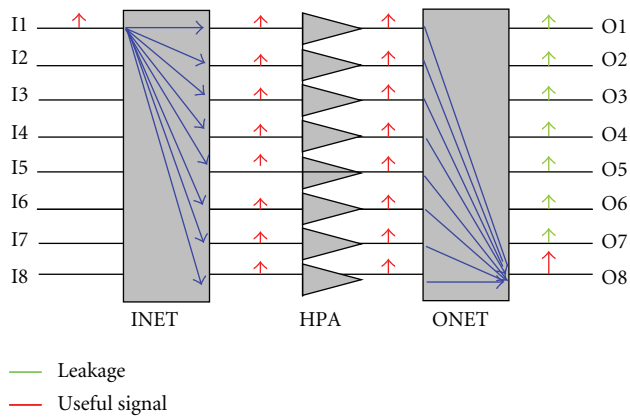

Figure 1: Block diagram of an 8×8 MPA with one carrier applied at the input port 1.

As shown in Figure 1, in ideal conditions, a signal applied at a single input port of the MPA is power-split and phase-shifted by the INET so that it can be amplified by all the HPAs and then properly recombined by the ONET into a single output port. However, in real cases, HPAs characteristics may differ from each other due to hardware imperfections, variation of thermal conditions, and aging. As a consequence, amplitude and phase errors occur, which, in turn, cause leakage of power in the unwanted output ports. Such a power leakage is kept under control in order to avoid significant performance degradation of the communication link. The reference MPA adopted for the analysis presented in this paper is an 8×8 MPA with input/output multiport networks based on Egami/Kawai definition [3]. This configuration of the INET/ONET is particularly efficient in terms of hardware reduction; it differs from the Butler matrix configuration [4] in the fact that intermediate phase shifters in the networks are completely avoided. As a reference, the phase and amplitude matrix relationships of the INET/ONET networks are provided here below:

$$\overline{\overline{\mathrm{ONET}}}_{\mathrm{PH}} = \overline{\overline{\mathrm{INET}}}_{\mathrm{PH}} = \begin{vmatrix} 0 & 90 & 90 & 180 & 90 & 180 & 180 & -90 \\ 90 & 0 & 180 & 90 & 180 & 90 & -90 & 180 \\ 90 & 180 & 0 & 90 & 180 & -90 & 90 & 180 \\ 180 & 90 & 90 & 0 & -90 & 180 & 180 & 90 \\ 90 & 180 & 180 & -90 & 0 & 90 & 90 & 180 \\ 180 & 90 & -90 & 180 & 90 & 0 & 180 & 90 \\ 180 & -90 & 90 & 180 & 90 & 180 & 0 & 90 \\ -90 & 180 & 180 & 90 & 180 & 90 & 90 & 0 \end{vmatrix}, \tag{1}$$

$$\overline{\overline{\mathrm{ONET}}}_{\mathrm{AM}} = \overline{\overline{\mathrm{INET}}}_{\mathrm{AM}} = \frac{1}{\sqrt{8}}\overline{\overline{\mathrm{ONES}}}. \tag{2}$$

The overall complex input multiport network is simply given by

$$\overline{\overline{\mathrm{INET}}} = \overline{\overline{\mathrm{INET}}}_{\mathrm{AM}} \bullet \exp\left(j\frac{pi}{180}\overline{\overline{\mathrm{INET}}}_{\mathrm{PH}}\right) \tag{3}$$

and the overall complex output multiport network, $\overline{\overline{\mathrm{ONET}}}$, can be expressed in an manner equivalent to (3).

The operator "$\bullet$" in (3) denotes the Hadamard element-wise matrix product; the $\overline{\overline{\mathrm{ONES}}}$ matrix introduced in (2) represents an 8×8 matrix with all the elements equal to 1. By indicating with $\overline{\overline{\mathrm{A}}}$ a diagonal matrix whose elements a_{ii} are the equivalent complex gains of the ith amplifier, it is possible to determine the vector $\overline{y}$ of the MPA output signals as a function of the input vector $\overline{x}$:

$$\overline{y} = \overline{\overline{\mathrm{ONET}}} \times \overline{\overline{\mathrm{A}}} \times \overline{\overline{\mathrm{INET}}} \times \overline{x}. \tag{4}$$

In an ideal case, being $\overline{\overline{A}} = a\overline{\overline{I}}$ (where a is the ideal amplifier gain and $\overline{\overline{I}}$ is the identity matrix), since $\overline{\overline{\mathrm{ONET}}} = \overline{\overline{\mathrm{INET}}}$, (4) can be simplified as follows:

$$\overline{y} = -ja \begin{pmatrix} 0 & \cdots & 0 & 1 \\ \vdots & \iddots & \iddots & 0 \\ 0 & \iddots & \iddots & \vdots \\ 1 & 0 & \cdots & 0 \end{pmatrix} \cdot \overline{x}. \tag{5}$$

Hence, if a signal is applied at the input port 1 of the MPA, its amplified replica shall appear at the output port 8 ($x = x_1 \rightarrow y_8 = -ja \cdot x_1$), as shown in Figure 1.

3. MPA Isolation Performance Analysis

For the MPA architecture shown in Figure 2, time domain simulations have been performed adopting baseband complex representation of the signals. For the evaluation of the isolation, a single continuous wave (CW) tone has been applied to port 1. Typical LTWTA AM/AM and AM/PM characteristics have been considered in the simulation. The working point of the HPAs has been set to 1.7 dB output back off (OBO), corresponding to about 4 dB input back off (IBO). Since the HPAs characteristics may differ from each other due to hardware imperfections, variation of thermal conditions, and aging, amplitude and phase mismatches/errors have been considered among the HPAs in order to assess the "leakage" of power in the unwanted output ports. As an initial assumption, for the sake of simplicity, amplitude and phase errors have been considered as Gaussian random variables with zero mean and standard deviation σ equal to 1/3 of the maximum error range deviation. For this analysis, no component imperfections of the INET/ONET have been taken into account, thus the relative scattering matrices have an ideal transfer function based on Egami-Kawai definition, as defined in (1) and (2). By using the Monte Carlo method, the cumulative distribution functions (CDFs) of the isolations have been derived for the cases

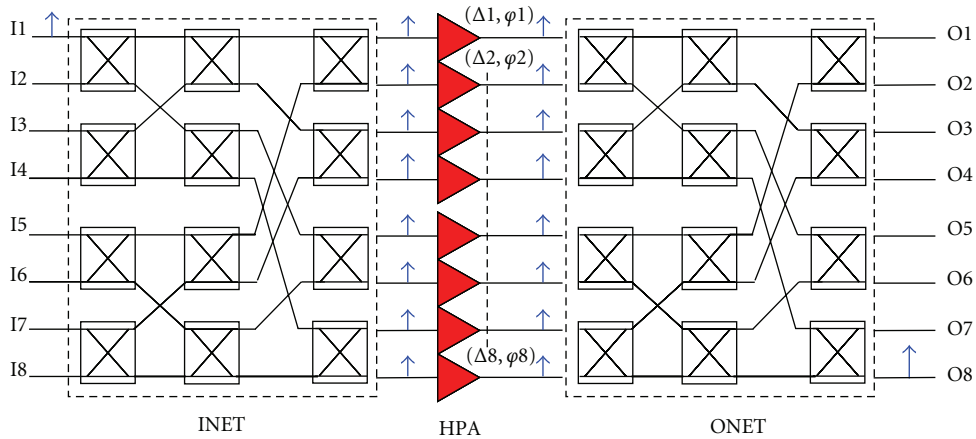

Figure 2: Reference 8 × 8 MPA block diagram.

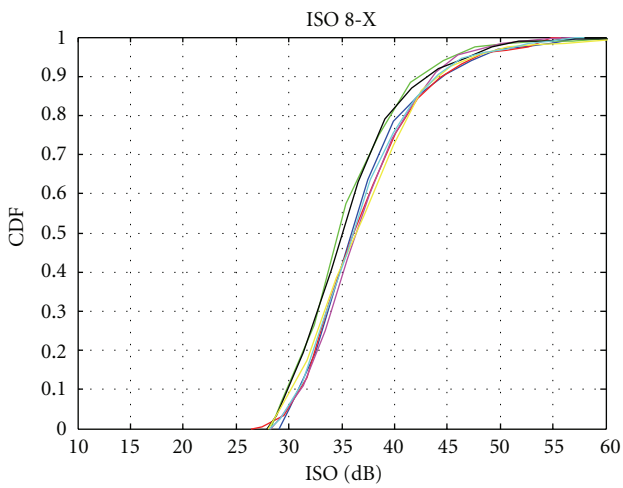

Figure 3: CDFs of isolation *ISO (8-j)* relative to HPAs amplitude/phase errors of case *a*.

Table 1: HPAs amplitude and phase tracking errors considered for each Monte Carlo simulation.

	Case *a*	Case *b*	Case *c*	Case *d*
Gain error (dB), ($\pm 3\sigma$)	±0.3	±0.5	±0.6	±1
Phase error (deg), ($\pm 3\sigma$)	±2	±3.5	±4	±7

shown in Table 1, where the HPAs amplitude and phase tracking errors are progressively increased from case *a* to case *d*.

The isolation parameter *ISO (8-j)* between output port 8 and output port *j* is defined as the ratio of the useful power at the wanted output port 8 and the power leakage present at output port *j*.

The statistical distribution of the isolations between the output port 8 and any other output ports (which, in ideal conditions, will have no signal leakage coming from the input port 8) is shown by the different colors/lines in Figure 3. The considered HPAs amplitude and phase tracking errors are, respectively, ±0.3 dB and ±2 deg (i.e., case *a* in Table 1).

Table 2: Simulation results of the isolation parameter ISO (corresponding to CDF ~ 0.6) benchmarked against literature values [3].

	Case *a*	Case *b*	Case *c*	Case *d*
ISO (Egami-Kawai) (dB)	38.1	33.3	32.1	27.2
ISO (simulated) (dB)	37.7	32.9	31.9	27

Figures 4, 5, and 6, show the statistical distribution of the isolations between the output port 8 and any other output ports for the other three cases in Table 1 (cases *b*–*d*, resp.).

For the four cases shown in Figures 3–6, it can be seen that the 90% isolation (CDF = 0.1) ranges from 20 dB in the worst-case HPAs amplitude/phase tracking errors (case *d*) to 31 dB for the smallest HPAs amplitude/phase tracking errors (case *a*). Table 2 shows how the simulation results corresponding to CDF ~ 0.6 compare to literature analytical data [3]: an excellent agreement is found, with an absolute difference ranging from 0.2 (case *c* and *d*) to 0.4 dB (case *a* and *b*). As shown in the previous figures, the presented method allows characterizing the full statistics of the isolation performance and can be extended to the evaluation of isolation in the presence of modulated multicarrier signals. The proposed method is based on time domain simulations and allows characterizing the combined effect of multicarrier loading and nonlinear HPA behavior on the isolation performance, which is not possible by employing commonly used analytical methods (such as [3]).

4. Conclusions

This paper has presented the impact that the amplitude and phase tracking errors of the high power amplifiers within an 8x8 MPA have on the isolation performance of the MPA itself. The analysis has been performed by means of Monte Carlo simulation that allows analyzing the full statistics of the output signals and is therefore a powerful tool to characterize

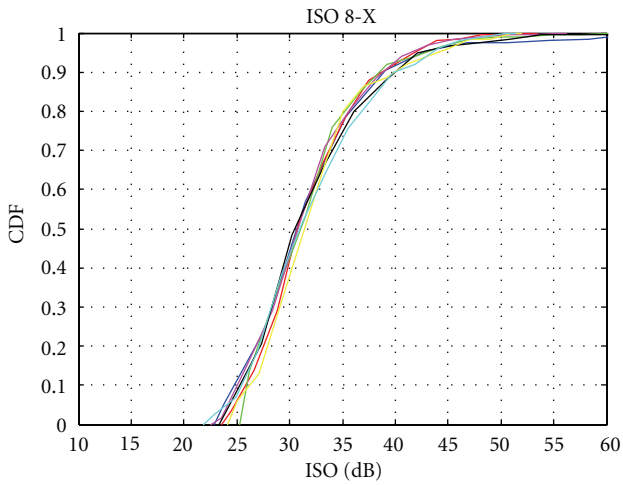

Figure 4: CDFs of isolation *ISO (8-j)* relative to HPAs amplitude/phase errors of case *b*.

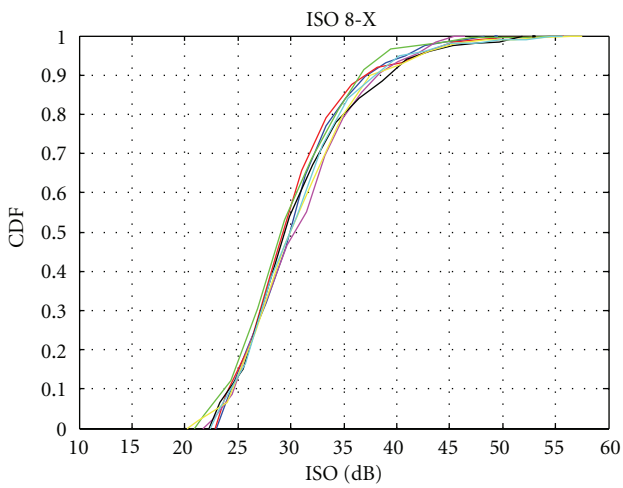

Figure 5: CDFs of isolation *ISO (8-j)* relative to HPAs amplitude/phase errors of case *c*.

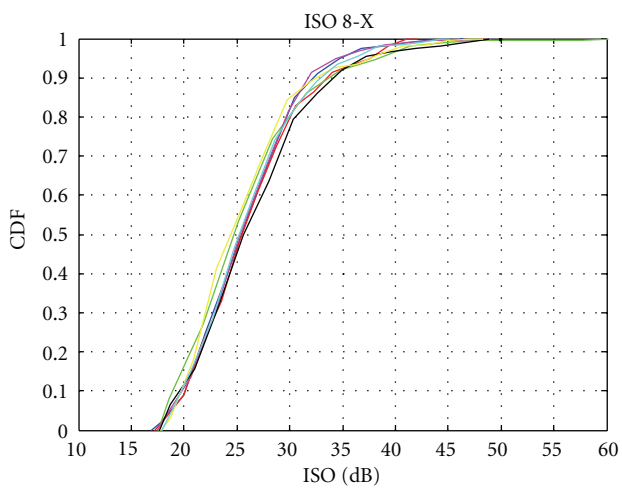

Figure 6: CDFs of isolation *ISO (8-j)* relative to HPAs amplitude/phase errors of case *d*.

the statistical behavior of the isolation for different HPAs amplitude/phase tracking errors.

Additional studies, based on the same statistical approach presented in this paper, can be carried out in order to evaluate how the overall MPA performance is further affected by hardware imperfections in the input and output microwave networks.

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