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Fast Automatic Analysis of Graceful Degradation in Power Combining Structures

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Abstract— Graceful degradation analysis in power combining structures is essential, but time consuming, when the number of combined ways is very large. The tool presented in this paper aims to automate the graceful degradation analysis when amplifiers fail or are switched off for output power flexibility or in phased array antenna applications. It is an alternative to commercial software as the tool highly reduces the designer operations by automating, for each number and combination of outages, the calculation of the 2-port scattering parameters of the whole structure. Therefore, the comparison between different isolation solutions of the combiner is made easier and faster. Simulation and comparison with measurements on a 16-way radial power amplifier in the Ka band are presented.

Keywords— graceful degradation; power combining; failure analysis

I. INTRODUCTION

Power combining techniques in Solid State Power Amplifiers (SSPA) are often required to reach high output powers, especially when the frequency increases due to the degradation of the power handling capability of semiconductor devices. Amplifier modules can be combined using conventional techniques based on corporate (or tree) structures like 2-way Wilkinson divider/combiner or, for a large number of combined amplifiers, using spatial and radial power combining to overcome the combining efficiency degradation in corporate structures [1]. In radial structures, the divider and the combiner are symmetrical and, to obtain the maximum combining efficiency, the N ways (including the individual amplifier) must be equi-phase and equi-magnitude with minimal losses in the combiner for maximum output power.

In case of amplifier failure or switch-off for power flexibility, the “off” amplifier(s) might strongly degrade the power combining of the remaining ways, depending on the impedance of the failed devices and on the combiner S-parameters [2]. To control the degradation, the divider/combiner can be optimized in terms of isolation between the ways without increasing the loss level.

In active phased arrays, distributed power amplification systems are often used in order to achieve significant radiated power levels. Several power amplifiers feed a single or a group of radiating elements in antennas designed for satellite or radar applications. In such systems, it is essential to analyze the impact of the failure of one or several amplifiers because such failures jeopardize the overall radiation pattern, leading, for instance to the increase of the side lobe levels.

An automatic tool was developed to analyze the impact of all the possible power amplifier failures on a divider/amplifiers/combiner structure, or on antenna array, depending on the number of failure cases and their combination. The algorithm is based on the flow graph theory, i.e. Mason’s rules [3] and is a enhanced, simpler and faster version of the software previously presented in [4]. In section II, the algorithm which calculates the S-parameters of the equivalent 2-port network in any failure case is presented. In section III, the simulation results are compared with measurement results of a 16-way radial power divider/combiner with improved isolation.

II. ALGORITHM

A. Flow graph and Mason gain

The graph flow of an N-way divider/combiner structure is based on S-parameters and includes nodes (waves a and b) and oriented transitions (or branches) with gain given by S_{nm} . In order to compute the four S-parameters of the system made up by the divider, amplifiers and combiner, the Mason gain formula algorithm was implemented as described in [3].

Using the example depicted on Fig. 1, the calculation of the four S-parameters is done by computing the path gain between the nodes D-A, J-A, D-G, J-G with a matched load connected between the nodes G-J to compute S_{11} and S_{21} and D-A to compute S_{12} and S_{22} .

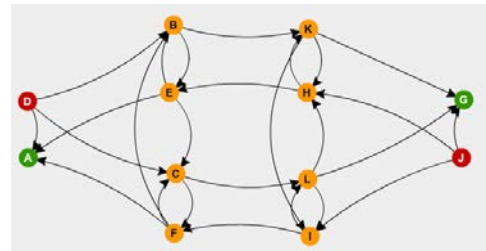


Fig. 1. Example of a flow graph of a 2-way divider/combiner structure

To calculate the path gain, the following data should be derived:

- the paths between every couple of nodes for which the gain is to be calculated (to compute the numerator of the Mason gain formula),
- the loops in the graph,

- the N-order loops. An N-order loop is composed of N non-touching loops (denominator of the Mason gain formula)

The complexity of the graphs rapidly increases with the number of ways. Table I presents the number of paths connecting each couple of the nodes for which the gain should be computed. The number of loops is also provided in the last column. In there, the N-order loops are separated by a comma, i.e. for the 2-way power divider/combiner there are 18 loops in the graph; then, 21 combinations of two non-touching loops are possible; similarly, 8 combinations of 3 non-touching loops can be made and finally only one 4-order loop is possible by combining 4 non-touching loops.

TABLE I. NUMBER OF PATHS AND LOOPS

Ways	S11 Paths	S12 Paths	S21 Paths	S22 Paths	Summation of N-order loops
2	23	12	12	23	$\Sigma (18, 21, 8, 1) = 48$
3	421	255	255	421	$\Sigma (193, 370, 257, 88, 15, 1) = 928$
4	13941	7168	7138	13941	$\Sigma (4324, 10226, 9360, 4583, 1352, 242, 24, 1) = 30112$

The results show an exponential increase of the number of paths connecting every couple of nodes for which the gain is required. A faster increase is observed in the number of loops. The impact of such exponential increase is direct on the computation time and resources required to execute the algorithm. Therefore, alternative ways to simplify the graph are proposed. Table II summarizes the equivalent data when perfect isolation is supposed between consecutive outputs of the power divider and combiner.

TABLE II. NUMBER OF PATHS AND LOOPS WITH PERFECT ISOLATION

Ways	S11 Paths	S12 Paths	S21 Paths	S22 Paths	Summation of N-order loops
2	5	2	2	5	$\Sigma(6, 11, 6, 1) = 24$
3	7	3	3	7	$\Sigma(9, 30, 45, 30, 9, 1) = 124$
4	9	4	4	9	$\Sigma(12, 58, 144, 195, 144, 58, 12, 1) = 624$

The significant simplification of the graph is reflected on the reduction of the number of paths and loops for the cases evaluated. However, this reduction penalizes the generalization of the algorithm applicability to non-isolated power dividers and combiners.

Additionally, this method remains complex and time-consuming, especially for higher number of ways. The 8-way case was executed and the summation of the N-order loops was found to exceed 390 000.

Given the obtained results, computation time and memory consumption, an alternative way was explored to calculate the S-parameters of the system.

B. Graph reduction approach

This method proposes the simplification of the graph flow using the elimination of hybrid nodes and of series, parallel and feedback connections [3].

From the graph example depicted on Fig. 1 where nodes B-E-K-H and nodes C-F-L-I represent two amplifiers, the nodes can be classified as follows:

- node of reflected waves: a node for which all the signals are incoming – (nodes: A and G).
- node of incident waves: a node with only outgoing signals – (nodes: D and J).
- hybrid node: the node presents simultaneously incident signals and reflected signals – (nodes: B, C, E, F, H, I, K, L).

The graph simplification is based on the hybrid node elimination and on the connection reduction. This procedure is illustrated on Fig. 2. Removing a hybrid node leads to a number of transitions which is equal to the number of incoming transitions times the number of outgoing transitions. The gain of the new branches is given by the product between the scattering parameters (i.e. branch gains S_k).

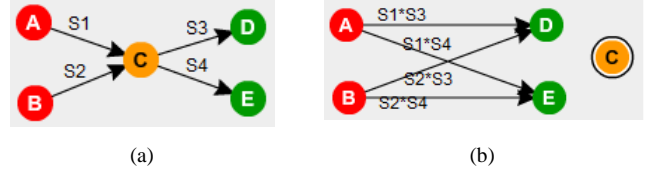


Fig. 2. Graph with (a) an hybrid node D, (b) C is removed and the graph is rearranged

An hybrid node elimination can also lead to a new self-(node)-loop connection, which can be reduced by using the rule illustrated on Fig. 3. In there, the graph can be seen as a subsystem with positive feedback having direct path gain equal to 1 and feedback path gain equal to $+S3$.

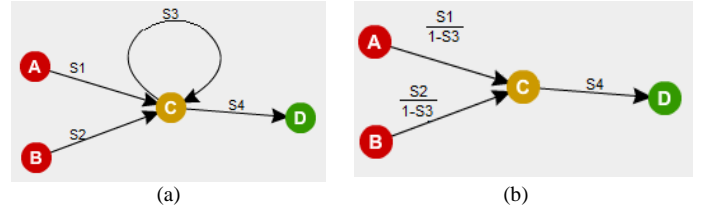


Fig. 3. Graph with (a) a self loop connection on node C, (b) loop removing and branch gain modifications

The elimination procedure is applied to all the hybrid nodes, leading to an equivalent graph that is indeed a 2-port network.

C. Algorithm implementation

The algorithm is implemented in C++ and all the inputs are touchstone files. One corresponds to the power divider; two describe the power amplifier performance under normal operation and when they are damaged or switched-off; the last touchstone file corresponds to the power combiner.

The implemented application automatically computes all the combinations of failure/switch-off cases to obtain the equivalent 2-port S-parameters of each configuration. Each transition is described by a source node, a destination node and a transition gain. The main steps of the algorithm are described on Fig. 4.

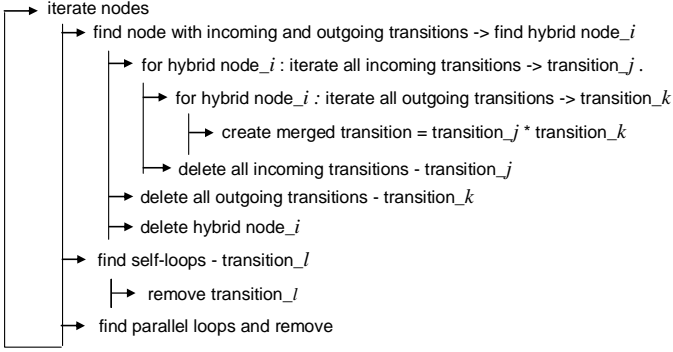


Fig. 4. Main steps of the algorithm

The algorithm is tested with two amplifier configurations: the first one uses an ideal 16-way Wilkinson corporate structure and the second one, a 16-way radial structure.

III. SIMULATION RESULTS

A. Ideal 16-way Wilkinson corporate structure

The theoretical output power P_{out} of a combiner, when m amplifiers are out of operation, is given by $P_{out} = P_{max}(1-m/N)$ where P_{max} is the maximum output power when all the N amplifiers are in operation [5]. Combining $(N-m)$ individual matched amplifiers, with power gain G_{pA} , in a matched divider/combiner structure, and assuming a linear behavior, the power gain G_p is given by:

$$G_p = |S_{21}|^2 = G_{pA} \cdot \left(1 - \frac{m}{N}\right)^2 \quad (1)$$

Therefore, G_p is calculated from the S_{21} parameter of the reduced graph as explained in the previous section. Equation (1) shows that the power gain is divided by 4 (i.e. decreased by 6 dB) when half of the amplifiers are out of operation.

As an example, the algorithm was tested on a 16-way corporate structure without and with isolation. The divider/combiner is based on 2-way Wilkinson dividers as shown in Fig. 5. Resistors are connected between the output ports of each divider for maximum isolation.

For graceful degradation analysis, the 16 individual amplifiers, connected between each port of the divider and the combiner, are considered to be identical, with S-parameters obtained from measurement. This is valid for both operation conditions, namely normal operation and damaged or switched-off. The calculations are done at a single frequency and each combination of m amplifiers out of operation is evaluated.

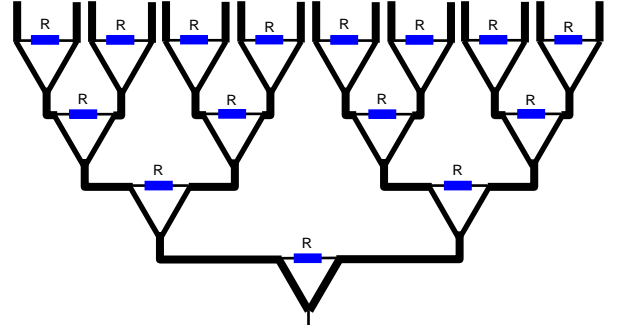


Fig. 5. 16-way divider based on 2-way $\lambda/4$ Wilkinson dividers with isolation resistors ($R=100\ \Omega$ for uniform divider) or without ($R = \infty$)

Without taking into account the N-way divider/combiner symmetries, the total number of combinations is given by $C_N^m = N! / m!(N-m)!$

To reduce the number of combinations tested, a file with the desired combinations for each case of failed or switched-off amplifiers can be defined and read as input data. Table III summarizes the number of failure cases and computation time (on a computer with 4 Go RAM and 3 GHz CPU) with $m = 1$ to 8 switched-off amplifiers.

TABLE III. NUMBER OF COMBINATIONS AND COMPUTATION TIME (N = 16)

m	1	2	3	4	5	6	7	8
C_N^m	16	120	560	1820	4368	8008	11440	12870
time (s)	0.64	5	30	125	320	603	790	902

The results obtained from the graceful degradation analysis, for the non-isolated Wilkinson corporate structure with 16 measured power amplifiers, are depicted on Fig. 6. Of course, with the perfectly isolated divider/combiner Wilkinson structure, the curve fits with (1). Gain variations between 0.5 dB and about 2.5 dB are observed, depending on the number of switched-off amplifiers. Nevertheless, much higher gain variations could be observed if all the amplifiers were not exactly identical.

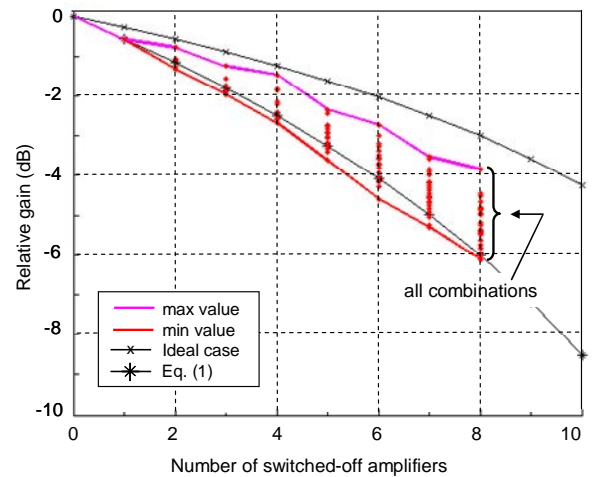


Fig. 6. Graceful degradation analysis of a 16-way non isolated Wilkinson corporate structure with measured amplifier S-parameters

B. Comparison with measurements

The algorithm was tested on a 16-way radial power divider/combiner with amplifier modules. The radial amplifier is described in [6]. It is made of a radial divider, based on a parallel-plate non-resonant cavity, superposed with an identical combiner (see Fig. 7). The algorithm results were compared with measurements in the Ka band (35-36.5 GHz).

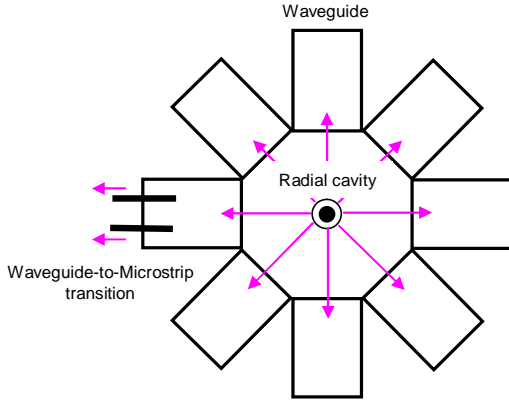


Fig. 7. 16-way radial divider made up by a non resonant radial cavity, 8 rectangular waveguides and 2 waveguide-to-microstrip transitions in each output waveguide.

Two versions of the divider/combiner are analyzed in terms of graceful degradation: one has a ‘natural’ isolation between the different ways (from -6 dB to -25 dB); the other one has an improved isolation (from -13 dB to -36 dB) thanks to absorbing material.

Only the radial amplifier with a 16-way divider/combiner with improved isolation was manufactured and tested. For simplicity, the ‘s17p’ Touchstone files used in both cases to analyze the graceful degradation, were obtained from HFSS simulations, which were validated through measurements [6].

The simulated graceful degradation at 36 GHz, with 1 to 8 switched-off amplifiers, is compared with measurements on Fig. 8. The minimum and maximum simulated values of the gain are also depicted for each combination. The measured switch-off combinations (up to 4 amplifiers) are: 1, 1-9, 1-5-9, 1-5-9-13. The latter corresponds to switched-off amplifiers that are equally spaced around the radial structure. The results from these simulations are very close to the measured gains, as shown in Table IV. Thanks to the improved isolation, the variation of the graceful degradation, depending on the switch-off combination, is much lower and better controlled than for the case of a structure with natural isolation.

TABLE IV. MEASURED AND SIMULATED GAIN OF THE 16-WAY RADIAL POWER AMPLIFIER AT 36 GHz

Combination	1	1-9	1-5-9	1-5-9-13
Measured gain (dB)	15.91	15.36	14.70	13.90
Simulated gain (dB)	16.2	15.74	15.07	14.45

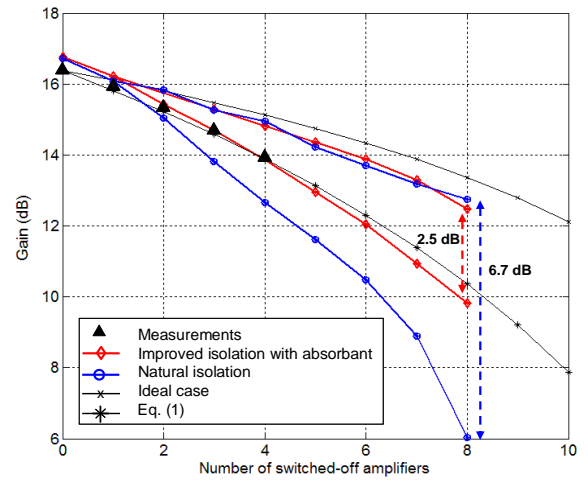


Fig. 8. Graceful degradation at 36 GHz of the 16-way radial amplifier: comparison between simulation of an isolated and a non-isolated divider/combiner structure and measurements (improved isolation case only).

IV. CONCLUSION

A tool for fast automatic graceful degradation analysis has been presented. It is based on the S-parameters of the divider/combiner and amplifier modules. It highly reduces the failure analysis procedure by automating the calculation for all the power amplifier failure combinations. Therefore, the study of different combiner isolation cases can be easily and rapidly carried on. Comparison between simulations and measurements of a Ka-band 16-way radial power amplifier has been presented.

An ongoing code improvement is the import of the S-parameters of N different amplifier modules (ON/OFF/failed amplifiers). Additionally, simulating the output power degradation when the power amplifiers operate in non-linear region, using a behavioural model, is also under consideration.

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