Measurement Analysis of Active Standing Wave Ratio on Networks with a Four-Port Vector Network Analyzer

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Fifth Sino-French Workshop on Information and Communication Technologies
SIFWICT 2019 - June 21, 2019, Nantes, France

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***Abstract*—The measurement of the active Standing Wave Ratio (SWR) of an antenna array poses an important problem since it requires, for a correct evaluation, to take into account the simultaneous excitation of the various elements that compose it. Indeed, the reflection coefficients obtained for each element when the other elements are powered differ from those obtained by a passive measurement because of the different interactions between the elements. In this paper, we show that the active SWR parameters obtained by using the passive distribution matrix do not correspond to the actual values obtained during a simultaneous excitation of all the elements. A true active SWR measurement procedure is then developed using the potential of a four-port vector network analyzer having two synchronizing internal sources.**

***Keywords*—Active SWR, antenna array, passive S parameters, input impedance.**

I. Introduction

From a circuit point of view, an antenna is characterized from its distribution matrix, commonly called S parameter matrix. The procedure for measuring such parameters (return loss or reflection coefficient) of an elementary antenna does not pose any problems and any vector network analyzer (VNA) can be used. In the case of an antenna array, the evaluation of the reflection coefficient of each elemental antenna is more difficult. By definition, the reflection coefficient of an antenna is evaluated when all the other sources are off:

$$s_{ii} = \left.\frac{b_i}{a_i}\right|_{a_j=0} \tag{1}$$

However, in the case of the networking of several elements, all are ultimately excited simultaneously by the same source, possibly out of phase and attenuated at the level of the unit radiators, depending on the desired radiation pattern. Each of these elements thus interacts with the others (proximity coupling, radiation coupling,...) and the reflection coefficient observed at the level of each element evaluated by a passive approach is no longer representative of reality. It is therefore necessary to implement a rigorous method for measuring this so-called active SWR.

One of the classical methods commonly used in the literature to evaluate active S parameters is by equation 2:

$$active\_S_{mn} = \frac{\sum_{i=1}^{N} S_{mi} a_i}{a_n} \tag{2}$$

Where S_{mi} denotes the mutual coupling between the m^{th} and the i^{th} element, a_i is the excitation of the i^{th} element and N is the total number of elements of the array.

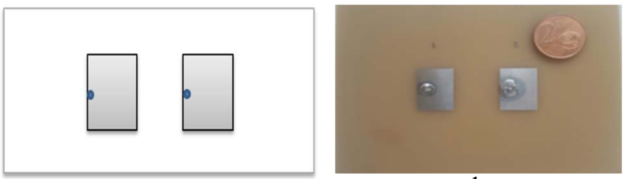
It is then possible, by measurement of the passive distribution matrix of the network to have a first evaluation of the active SWR. Unfortunately, this approach is limited since it only considers first-order interactions. The latter therefore poses a problem for taking into account the simultaneous operation of the constituent elements of the array. In other words, the passive matrix analysis does not accurately represent the actual power waves on the ports of the supply network when all the elements are excited simultaneously. A full active S parameter analysis is therefore necessary.

A measurement method has been proposed in [1] for evaluating such active S parameters using a two-port VNA. The latter is based on the measurement of a transmission coefficient in a configuration using a coupler and a balanced power divider. Calibration is first necessary in order to compensate for some of the errors introduced in the measurement. However, the accuracy of the measurement remains intrinsically linked to the quality of the directional coupler which theoretically must have infinite directivity. In addition, the use of the balanced power divider introduces an imprecision as to the control of the phase at the level of the excited elements, which can pose problems of its validity.

In this paper, we propose a measurement methodology based on the use of a four-port network analyzer to evaluate active S parameters of an antenna array. The measurement protocol is thus explained in terms of calibration and avoids the ambiguity of the use of the coupler and the power divider.

II. 3D SIMULATION & MEASUREMENT

For the sake of consistency, we will first compare the results obtained by a 3D modeling approach under ANSYS HFSS with the passive measurement of a network of two elements arranged according to the plan E configuration (Fig.1-a). For the evaluation of the active SWR, we will use equation (2). The operating frequency is arbitrarily chosen at 5GHz. Each element is then optimized to have input impedance close to 50Ω at the operating frequency. The results are shown in TABLE I. Column A of this table gives the input impedance of each antenna obtained by a passive distribution matrix approach while column B gives the values of the input impedance when the two elements are excited (Eq.2). Despite the fact that both antennas are modeled with the same dimensions, we observe a slight difference for these two situations. This is mainly related to the mesh process which introduces a different mesh on the two antennas. Anyway, we observe a decrease in the impedance seen at the entrance of the two antennas in active mode. This reflects the importance of active SWR in antenna networks.



a b

Fig. 1. Two elements arranged in plan E configuration

TABLE I. NORMALIZED INPUT IMPEDANCE VALUES VIA HFSS; A)PASSIVE INPUT IMPEDANCE B) ACTIVE INPUT IMPEDANCE.

Input impedance in Ω @ 5GHz	**A) Zin passive**	**B) Zin active**
Antenna 1	(52.72-j0.50) Ω	(43.62-j6.75) Ω
Antenna 2	(51.67+j0.39) Ω	(42.86-j5.81) Ω

An embodiment of this network of two elements arranged along the plan E is given in Fig. 1-b. The measurement is then carried out in two stages using the Rohde & Schwarz ZVA 24 vector network analyzer [2] previously calibrated in the antenna access plan (calibration kit Rohde & Schwarz kit ZV-Z135).

First, the passive S parameters are determined using two VNA ports [3] and the corresponding denormalized impedance is recorded in TABLE II (column A). The value of the impedance is extracted directly by observing the associated Sii parameter on the Smith chart (Fig.2) at the optimum operating frequency of the antenna. In our case, due to inaccuracy of etching, the antennas resonate at a slightly higher frequency i.e 5.06GHz. This error is minimal and does not affect the relevance of the observed results. The denormalized input impedance (column B) is evaluated according to equation 2.

In both cases of 3D simulation and measurement, the mutual coupling remains under 20 dB at the selected frequency (Fig. 3).

In a second step, the network analyzer is set to coherent mode. In this mode of operation, the input impedance is extracted from the observation of the fraction $\left.\frac{b_1}{a_1}\right|_{a_2\neq 0}$ on the Smith chart and is recorded in TABLE II (column C). TABLE II shows that when both antennas are lit simultaneously, the measured input impedance (column C) of the two antennas decreases. This decrease in impedance is close enough to the values obtained in column B.

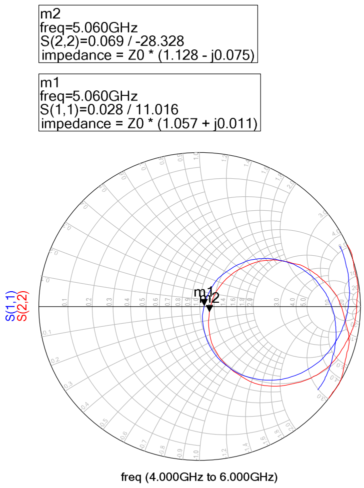


Fig. 2. Smith chart for two elements

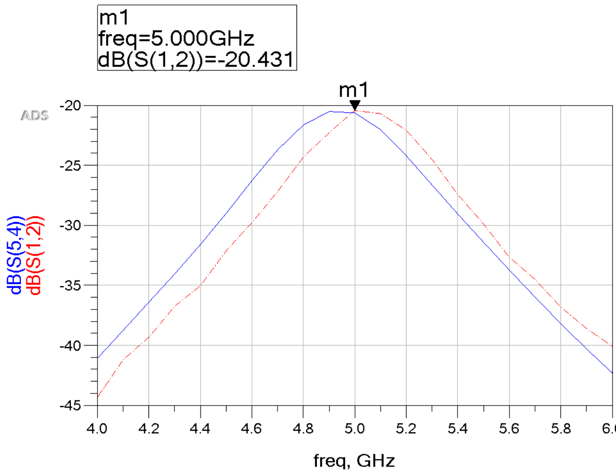


Fig. 3. Mutual coupling per simulation (blue curve) and measurement (Red curve)

TABLE II. DENORMALIZED INPUT IMPEDANCE VALUES OBTAINED BY MEASUREMENT.

Input impedance in Ω @ 5.06GHz	**A) One antenna is powered on**	**B)Zin active according to equation2**	**C) All antennas are powered on**
Antenna 1	(52.8+j0.5)Ω	(47.5-j8.60)Ω	(46.9-j8.81)Ω
Antenna 2	(56.4-j3.7) Ω	(49.8-j12.9) Ω	(50.1-j12.7)Ω

This preliminary work shows that measurement of active SWR does not pose any problem with two antennas, however, when it comes to significant number of antenna array elements then the effect can be more noticeable. Therefore, in order to demonstrate the effect of active SWR, we next proceed to more than two elements.

The same procedure is extended to four antenna elements arranged in plan E formation and the 3D simulation results are tabulated in TABLE III.

Table III(column A) shows the values obtained through Eq.1.Here, the antennas present a different value than 50Ω and it is probably due to proxy of antenna elements. The antennas (1 and 4) and antennas (2 and 3) present also a slightly different value which is due to the introduced mesh. Column B shows the results of active SWR (Eq. 2) where the impedance is observed to decrease.

TABLE III. DENORMALIZED INPUT IMPEDANCE VALUES VIA HFSS; A) PASSIVE INPUT IMPEDANCE B) ACTIVE INPUT IMPEDANCE

Input impedance in Ω @ 5GHz	A) Zin passive	B) Zin active
Antenna 1	(54.75-j0.07)Ω	(48.96-j3.84)Ω
Antenna 2	(52.89-j1.11)Ω	(40.89-j5.05)Ω
Antenna 3	(52.58-j0.90)Ω	(41.24-j6.91)Ω
Antenna 4	(53..80+j1.6)Ω	(48.47-j2.71)Ω

The measurement procedure is now extended for the active SWR of an antenna array with four elements (Fig. 4). A balanced power divider allows the coherent excitation of the antennas. A prior measurement of each of the transmission coefficients of this power divider and the associated coaxials makes it possible to validate the equilibrium of the amplitudes and phases at the accesses (Terminal d) of the antennas. This measurement also makes it possible to compensate the amplitude and the relative phase at the level of the antenna to be measured by controlling the parameters of the source associated with this port (accuracy about 0.1dB in magnitude and 1° in phase).

A patch antenna array of four elements along plan E is fabricated. Frequency of 5.06GHz is chosen as the best tradeoff frequency according to the realized array as previously in case of two antennas.

Measurements are carried out again in two steps. Firstly, individual antennas are powered with 1 milliwatt one by one. The input impedance of each antenna is then recorded from passive return loss measurement in TABLE IV (Column A). It can be observed that, as for simulation, a symmetrical behavior is observed and the input impedance of all antennas remains quite close to 50Ω at the chosen frequency. TABLE IV (Column B) shows the input impedance evaluated according to Eq. 2 where the impedance shows a decreased value.

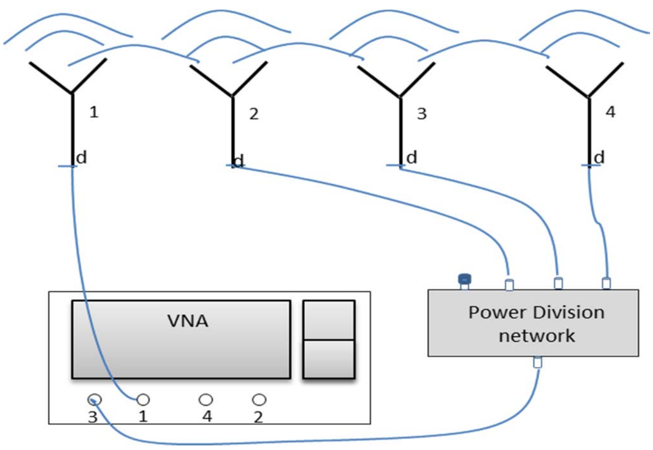


Fig. 4. Active SWR Measurement scheme for a 4-element array

Secondly, all antenna elements are powered together simultaneously according to coherent mode. In accordance with Fig. 3, both ports of VNA are set to coherent mode and each antenna impedance is recorded in column C. The screen shot of the measurement setup is shown in Fig.5. It can be observed that the obtained results present decreased impedance which is slightly different than the values obtained via Eq.2 (Column B). This slight change in impedance is due to higher order interaction of power waves unlike that of Eq.2 where there is only first order interaction being involved. However, the change in impedance can be more considerable if higher number of antenna elements operates simultaneously.

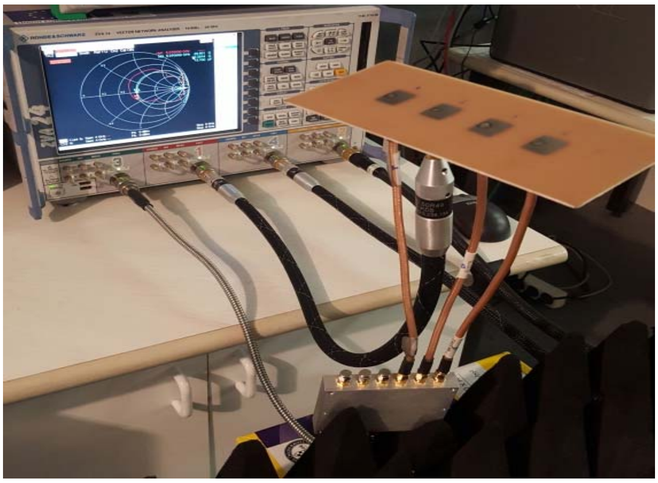


Fig. 5. Measurement setup for a 4-element array in coherent mode

TABLE IV. DENORMALIZED INPUT IMPEDANCE VALUES OBTAINED BY MEASUREMENT.

Input impedance in Ω @ 5.06GHz	A) One antenna is powered on	B)Zin active according to equation2	C)All antennas are powered on
Antenna 1	(46.3-j0.6) Ω	(43.55-j7.41) Ω	(44.85-j9.35)Ω
Antenna 2	(52.2-j1.15) Ω	(45.05-j15.42)Ω	(47.1-j17.7) Ω
Antenna 3	(52.25-j0.4) Ω	(45.25-j13.05)Ω	(46.15-j14.1)Ω
Antenna 4	(49.15-j0.5) Ω	(45.6-j6.31) Ω	(46.7-j8.22) Ω

Moreover, it can be noticed that when two antennas are set to observe their impedance in coherent mode, they show very minute change in impedance according to TABLE II (Column B&C), and this change in case of four antennas increases even a bit further according TABLE IV(Column B&C).It implies that this change may drastically increase if the number of antenna elements in an array is quite large. Thus, it is important to take into account the simultaneous excitation of antenna array for better realization of its active SWR.

III. CONCLUSION

A new method to measure active SWR has been proposed based on the simultaneous excitation of all elements of an antenna array by exploiting the capabilities of a vector network analyzer having two synchronizing sources. The advantage of this method is that it does not require any particular calibration. Moreover, this study has made it possible to highlight that the evaluation of the active SWR by a passive distribution matrix approach is perhaps no longer sufficient to translate the reality. Further work will have to be carried out for a better prediction of the active SWR in the case of a network with a large number of elements.

ACKNOWLEDGMENTS

Authors would like to thank Engr. Guillaume Lirzin and Engr. Marc Brunet for manufacturing antenna array prototypes.

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