Comparative analysis among frequency sampling algorithm applied in microwave measurements

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***Abstract*—This paper presents a comparative analysis between five algorithms. The goal of the algorithms was to reduce the acquisition time for high frequency measurements using Vector Network Analyzer. The proposed algorithms were developed by the authors and in this paper the accuracy and the execution time will be analyzed. The results will be presented in terms of information consistency and dynamic behavior. Finally, a classification between the five proposed algorithms using a key performance indicator will emphasize only one algorithm with high performances regarding the significant number of frequencies reduction, the decreasing of computation effort keeping the accuracy and the consistency of the initial device response.**

Keywords—microwave devices; signal sampling; reduced order systems; adaptive estimation; interpolation.

I. INTRODUCTION

In microwave measurements, Vector Network Analyzer (VNA) is the most popular instrument used to test different devices such as filters, cables, antennas, resonator, etc. [1 - 4]. Particular attention is paid for calibration procedure in order to keep a high level for the accuracy of the measurements [5 - 8].

One of the biggest problems involved by the VNA was the acquisition time. To reduce the time, there were developed algorithms based on orthogonal distance regression [9], algorithms built on multivariate optimization [10], algorithms based on the least mean squares method [11], algorithms developed on Fourier analysis [12], complex-value algorithms [13], algorithms which operate with spline interpolation technique [14], [15].

The algorithms were implemented with differed software intruments, such as Matlab, METAS VNA Tools II, METAS UncLib, Wincal XE, MultiCal, ANSYS HFSS, Advanced Design System, custom software etc. [16 - 22].

The algorithms was tested in different VNA areas. Some researchers developed multi-frequency extraction algorithm to determine the soil relative-dielectric-permittivity characterization in the 0.001-3 GHz frequency range [23] and others created error terms calibration algorithm of VNA based on the signal flow graph theory and the Mason formula [24].

Studies were made in introducing algorithms for the residual errors of S-parameter acquired with VNA and calibrated with standards or algorithms which simulate the residual errors based on its unknown frequency properties and known parameters [25 - 26]. Some algorithms are used with other methods, e.g. an estimation algorithm based on the quasi-optimal unscented Kalman filter which was used with a distance-frequency system model for calibrating the residual errors [27].

The VNA analysis a high frequencies range, starting with low frequencies (1-3 GHz) and up to 1.1 THz. One popular class of tested devices are the filters. Most used filters have a frequencies range between 2-15 GHz [28-30].

In this paper, will be presented a comparative analysis among five frequency sampling algorithms applied in microwave measurements with the main purpose to reduce the acquisition time.

II. THE STRUCTURE OF THE PROPOSED FREQUENCY SAMPLING ALGORITHMS

The proposed algorithms have the following objectives:

- Reducing the number of frequencies used for measurements. Consequently, the acquisition time will be reduced;
- Preserving the informational consistency by identifying all spikes.

Each frequency sampling acquisition algorithm (FSA) assumes the following steps:

- The factor, *fact*, is computed using relation (1) proposed below by the firs author.

$$fact = (f_{\max} - f_{\min}) \cdot 10 \ \ [GHz] \qquad (1)$$

where *fact* is the normalization factor;

f_{max} - maximum frequency;

f_{min} - minimum frequency;

The normalization factor is required to obtain the non-dimensional frequencies represented with the dimensional amplitudes in Cartesian coordinates.

- Initial frequencies are normalized with *fact* value using relation (2).

$$f_{i\_n} = \frac{f_i[GHz]}{fact[GHz]}[non-dimensional] \quad (2)$$

where $i = \overline{1,n}$

f_{i_n} – normalized frequency

f_i – initial list of frequencies

n – total number of initial frequencies list

- Computing the amplitude A_{11} using S-parameter S_{11} as presented in relation (3).

$$A_{11}(S_{11}) = \sqrt{Re(S_{11})^2 + Im(S_{11})^2} \; [non-dimensional] \quad (3)$$

- One of the five proposed FSA is applied;
- The non-dimensional normalized frequencies is converted back to GHz domain, by applying the same fact factor, using the relation (4).

$$f_i = f_{i\_n} \cdot fact[GHz] \quad (4)$$

where $i = \overline{1,m}$

f_i is the initial frequencies

m – the reduced number of frequencies used by FSA.

- Next, the m values obtained in previous steps are interpolated using the cubic spline method in order to reconstruct the original device under test (DUT) response.

III. The Proposed Frequency Sampling Algorithms

In this section presents a comprehensive presentation regarding the five proposed algorithms. Table 1 represents the algorithm name and abbreviation.

The Euclidean Distance Frequency Sampling Algorithm (EDFSA) consists in acquiring three equally distributed frequencies and the corresponding S parameters. In the following step, the Euclidean distance between is computed between two consecutive points and the maximum distance is find. In the next step, this Euclidean Distance is halved, and a new measurement is provided for the corresponding frequency value. Finally, all distances are recomputed and the maximum differences are identified, as already mentioned. In this way, the algorithm reduces the unknown behavior between two points by keeping a moderate points distribution [31].

TABLE I. THE PROPOSED ALGORITHMS ABREVIATION

Item	***The algorithm name***	***The algorithm abbreviation***
1.	The Euclidean Distance Frequency Sampling Algorithm	EDFSA
2.	Adaptive step-size algorithm	ASS
3.	Extreme points sampling algorithm	EPSA
4.	Spline frequency sampling algorithm	SFSA
5.	Improved rational interpolation model algorithm	IRIMA

The Adaptive step – size algorithm (ASS) consists in acquiring at the beginning only three points corresponding to the start frequency, start frequency plus a predefined step and start frequency and a double step size. Using these points, it is computed the first derivative, which is a line. The angle calculated as the intersection of the line with Ox has a value greater or lower than a threshold. If the angle is greater, than the step is increased. Otherwise, the step - size is decreased. Next, a new point is acquired using the last frequency plus the new step – size and the algorithm is applied until the new frequency is greater than the maximum frequency (stop frequency) [32].

The Extreme points sampling algorithm (EPSA) implies to choose both a sample of 5% are equally distributed frequencies from all frequencies and the corresponding amplitudes. Next, the coefficients of *N-1* polynomial function *f* are computed based on the *N* points (5% respectively). The value of amplitude for each frequency is computed based on the coefficients of the polynomial function *f* and the values obtained are approximated besides the real values. Further, the extreme values of the amplitude are identified in the list of the approximate values and the normalized frequencies and their amplitudes are detected for the extreme points. Then, the difference between the approximated and the measured value of amplitude is computed or each frequency. If the difference is higher than the compulsory value, then the algorithm resumes by adding each time the new normalized frequencies which correspond to the maximum and minimum points from the normalized frequencies list. The algorithm stops when no difference between the approximate and the measured values does not exceed the value set [33].

The Spline frequency sampling algorithm (SFSA) uses a predefined number of frequencies. Next, it is performed a spline interpolation and a linear interpolation between every two consecutive points. Then, it is computed the differences between the first interpolation and the second one. The maximum difference is identified, and a new point is acquired for the corresponding frequency. The algorithm is computed until all differences are lower than an imposed value [34].

The Improved rational interpolation model algorithm (IRIMA) computes the maximum difference between a rational interpolation model with k order and a previous rational interpolation model with $k-1$ order, where $k+1$ represents the number of evaluated frequencies [35].

IV. The Comparative Analysis

By reducing the number of frequencies, the accuracy of the measurements is considerably reduced. However, the author emphasizes that a non-uniform distribution of points, concentrated especially in spike areas, leads to a high accuracy closed enough to the original measurement. The comparative analysis of the five algorithms takes into account the following parameters:

- the global relative error that quantifies the informational consistency;
- the runtime that quantifies dynamic performance.

In order to compare the performance of each algorithm, the following mathematical method is proposed:

- the *error rate percentage indicator* is computed as the ratio of the global relative error ($e_{r_{glob}}$) of the analyzed algorithm and the maximum relative error ($e_{r_{glob\_max}}$) for each algorithm according to the relation (5):

$$ic_{er} = \frac{e_{r_{glob}}}{e_{r_{glob\_max}}} \cdot 100 \ [\%] \quad (5)$$

- the *percentage quality indicator of the execution time* is computed as a ratio between the execution time of the analyzed algorithm (te) and the maximum value of the exertion time using one of the five algorithms($\max(te)$), according to the following relation (6):

$$ic_{te} = \frac{te}{\max(te)} \cdot 100[\%] \quad (6)$$

- the weighted average of the two indicators is computed to obtain the *global quality indicator* expressed as a percentage (ic_{global}) according to the relation (7). Using this indicator, it is possible to perform a comparative analysis of the proposed algorithms. The global quality indicator takes into account a higher importance of the *error rate percentage indicator* (70% - ic_{er}) and a low importance for the *percentage quality indicator of the execution time* (30% - ic_{te}).

$$ic_{global} = \frac{70\% \cdot ic_{er} + 30 \cdot ic_{te}}{2}[\%] \quad (7)$$

Next, four examples will be presented as follows:

- Test 1 - a bandpass filter with the frequency range between 4.7 – 5.5 GHz, for 321 uniformly distributed frequencies;
- Test 2 - a bandpass filter with the frequency range between 13.5 – 15.5 GHz, for 400 uniformly distributed frequencies;
- Test 3 - a bandpass filter with the frequency range between 13.5 – 15.5 GHz, for 1600 uniformly distributed frequencies;
- Test 4 - a coaxial cable with the frequency range between 0.01 – 8 GHz, for 16000 uniformly distributed frequencies

A. Test 1

A bandpass filter with the frequency range between 4.7 – 5.5 GHz was analyzed using the results for each algorithm proposed. Relation (8), (9) and (10) presents an example for the proposed indicators using relation (1), (2) and (3). Similarly, it is computed for the other algorithms, obtaining the values presented in table 2.

$$ic_{er} = \frac{0.12}{0.49} \cdot 100 = 24.48\% \quad (8)$$

$$ic_{te} = \frac{1.07}{1.16} \cdot 100 = 92.24\% \quad (9)$$

$$ic_{global} = \frac{70\% \cdot 24.48\% + 30\% \cdot 92.24\%}{2} = 22.40\% \quad (10)$$

Table 2 depicts a classification score using the performance indicators as follows: best performing algorithm will receive 5 points and the lowest performance algorithm will receive only one point.

TABLE II. THE PROPOSED ALGORITHMS PERFORMANCE FOR 40 FREQUNCIES OUT OF 321 OF THE BANDPASS FILTER WITH THE FREQUENCY RANGE BETWEEN 4.7 – 5.5 GHZ

Algorithm	*Global relative error [%]*	*Execu-tion time [s]*	**ic_{er} [%]**	**ic_{te} [%]**	**ic_{global} [%]**	*Initial score*
EDFSA	1.07	0.12	24.48	92.24	22.4	3
ASS	0.18	0.48	97.95	15.51	36.6	2
EPSA	0.77	0.02	4.08	66.37	11.3	4
SFSA	**0.04**	**0.10**	**20.4**	**3.44**	**7.6**	**5**
IRIMA	1.16	0.49	100	100	50	1

The results presented in table I shows that the global quality indicator has the lowest value for the Spline frequency sampling algorithm points (SFSA).

Fig. 1 shows the dynamic performance graph of each algorithm applied to the filter with the 4.7 to 5.5 GHz frequency range, where it can be seen that the EPSA algorithm has the lowest execution time.

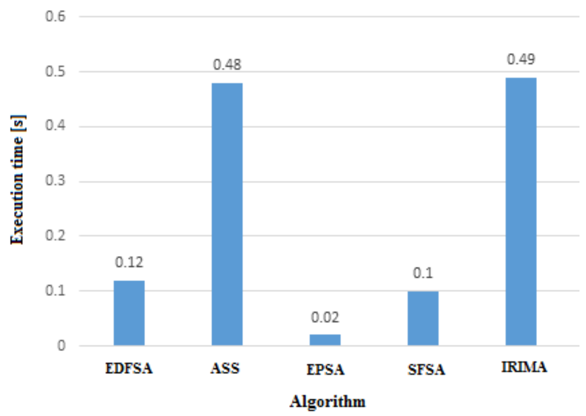

Fig. 1. The dynamic performance graph of each algorithm applied to the filter with the 4.7 to 5.5 GHz frequency range.

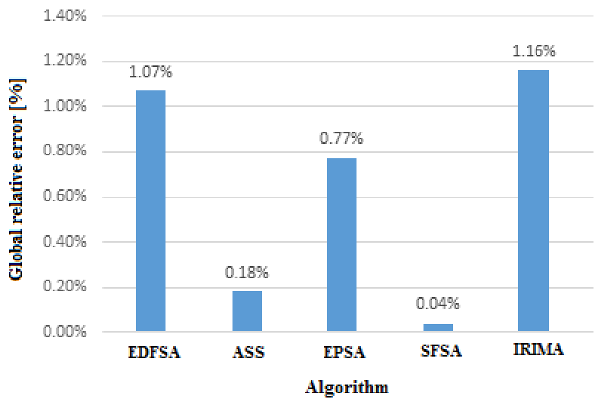

Fig. 2. The graph of global relative error of each algorithm applied to the filter with the 4.7 to 5.5 GHz frequency range

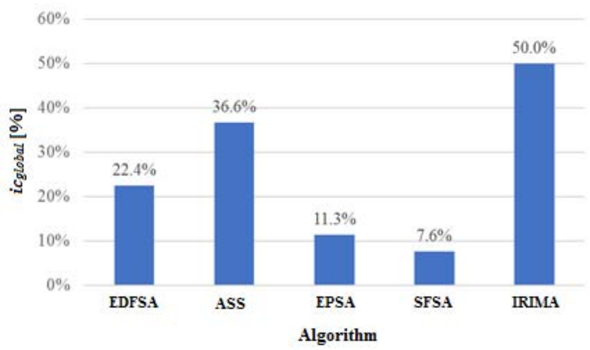

Fig. 3. The graph of global quality indicator of each algorithm applied to the filter with the 4.7 to 5.5 GHz frequency range

However, the IRIMA algorithm has a higher global relative error than the SFSA algorithm, as it can be seen in fig. 2.

Because it is more important to get a smaller global relative error besides the execution time, but also because the global quality indicator shows better results for SFSA, we propose that this algorithm is best suited for solving the improvement of the working speed of vector network analyzers, respectively VNAs (fig. 3).

B. Test 2

This test consists in the analysis of a [13.5, 15.5] GHz bandpass filter. Initially, 400 uniformly distributed frequencies in the specified range are used. In order to perform performance analysis, the algorithms assets only 50 frequencies. In table 3 it can be noticed that the global quality indicator has again the lowest value for the Spline frequency sampling algorithm (SFSA).

TABLE III. THE PROPOSED ALGORITHMS PERFORMANCE FOR 50 FREQUNCIES OUT OF 400 OF THE BANDPASS FILTER WITH THE FREQUENCY RANGE BETWEEN 13.5 – 15.5 GHZ

Algorithm	*Global relative error [%]*	*Execu-tion time [s]*	ic_{er} [%]	ic_{te} [%]	ic_{global} [%]	*Initial score*
EDFSA	29.53	0.16	100	32.65	40.03	1
ASS	1.57	0.49	5.31	100	16.85	3
EPSA	3.12	0.12	10.56	24.48	7.36	4
SFSA	**2.03**	**0.11**	**6.87**	**22.44**	**5.77**	**5**
IRIMA	5.18	0.46	17.54	93.87	20.21	2

C. Test 3

In this test, the same filter with the frequency range 13.5 - 15.5 GHz was analyzed. This time, 1600 uniformly distributed frequencies in this range are analyzed, so that an example with a much higher number of initial frequencies is also considered.

The performances of the five algorithms are analyzed for the reduced number of 100 frequencies from the 1600 initial ones, and the results are presented in table 4.

TABLE IV. THE PROPOSED ALGORITHMS PERFORMANCE FOR 100 FREQUNCIES OUT OF 1600 OF THE BANDPASS FILTER WITH THE FREQUENCY RANGE BETWEEN 13.5 – 15.5 GHZ

Algorithm	*Global relative error [%]*	*Execu-tion time [s]*	ic_{er} [%]	ic_{te} [%]	ic_{global} [%]	*Initial score*
EDFSA	27.84	0.53	100	100	50	1
ASS	0.49	0.48	1.76	90.56	14.2	3
EPSA	0.76	0.12	2.72	24.48	4.62	4
SFSA	**0.25**	**0.09**	**0.89**	**16.98**	**2.85**	**5**
IRIMA	0.94	0.53	3.37	100	16.17	2

Using these results, it can be noticed that SFSA offers again the best results analyzing global relative error, but also execution time.

D. Test 4

Table 5 presents the performances of the five algorithms for a coaxial cable with the frequency range between 0.01 - 8 GHz. For this example, the initial number of frequencies is 16000 and the reduced number of frequencies used for the algorithm comparison is 1000. Data in table 5 shows again that the SFSA has the best performance both in terms of the percentage quality indicator of the execution time and error rate percentage indicator. It can also be noticed that the IRIMA algorithm does not provide results because the computational effort is too high in relation to the 1000 required points.

TABLE V. THE PROPOSED ALGORITHMS PERFORMANCE FOR 1000 FREQUNCIES OUT OF 1600 OF THE COAXIAL CABLE WITH THE FREQUENCY RANGE BETWEEN 0.01 – 8 GHZ

Algorithm	*Global relative error [%]*	*Execu-tion time [s]*	*ic_{er} [%]*	*ic_{te} [%]*	*ic_{global} [%]*	*Initial score*
EDFSA	3.41	35.35	100	100	50	2
ASS	0.0056	1.02	1.64	2.88	1.00	3
EPSA	0.007	0.12	0.20	0.33	0.11	4
SFSA	**0.0068**	**0.09**	**0.19**	**0.25**	**0.10**	**5**
IRIMA	Out of memory					1

The comparative analysis shows that the Spline frequency sampling algorithm (SFSA) provides the best performance in terms of the execution time and global error. The computation effort is at a moderate value, and the samples have a distribution focused on areas of interest (represented by spikes).

Fig. 4 presents the total score obtained by summing the partial score of each algorithm and for each presented test

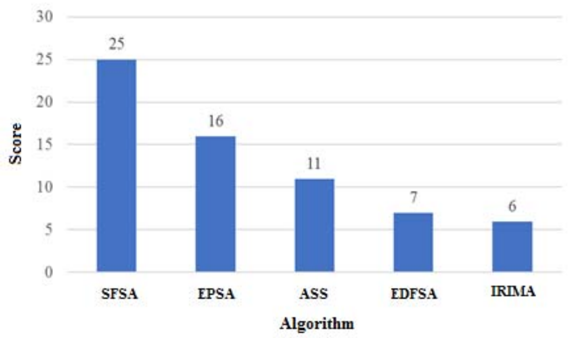

Fig. 4. Classification of algorithms according to the total score obtained for the tests performed

The algorithms are presented in order of the total score achieved. Fig. 4 shows that the SFSA and EPSA algorithms have the highest score.

V. CONCLUSION

The four tests were analyzed based on following indicators proposed by the authors: the error rate percentage indicator, the percentage quality indicator of the execution time, and the global quality indicator.

The results of the comparative analysis of the five algorithms pointed out the performances of Spline frequency sampling algorithm (SFSA) which means a high degree of confidence both in terms of information consistency and execution time. The authors indicate that this is the highest performance algorithm.

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