Data Processing in Multiport-based Reflectometer Systems

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Abstract. *The paper describes operations with DC output voltage of multiport-based reflectometer system. The proposed system is based on the same principle as common six-port systems; however the used coupler has more outputs. This allows extension of bandwidth and higher precision of the measurement. To process measured data, standard six-port system calculations are used. To get more accurate results than in the case of simple six-port system additional statistical methods were used. The higher number of outputs produces large amount of measurement and calibration data, however using described technique this amount of data were reduced.*

Keywords

Six-port reflectometer, vector scattering parameters measurement, microwave detector, diode detector.

1. Introduction

Vector scattering parameters measurement is a standard procedure in RF and microwave electronics. Of course, commercial vector network analyzers are usually used for this purpose. However, in some cases where this way is not applicable or economic, some other method can be used. This paper deals with one of the alternative methods, which is based on the six-port reflectometer. The principle of this method was first described by Engen [1] in 1977 and further in [2], [3]. There are many applications of this reflectometer system today. In the wireless communication [4], frequency multiplier monitoring [5], standard measurement [6] and more. It is evident that the reflectometer system is still up to date and has its applications. The main advantage of the system is its simple RF hardware. Vector value of reflection coefficient is computed on the basis of several (four) scalar values. That means usually voltages from power detectors. Nowadays the most common way of the measurement of the scalar values is the use of simple (Schottky) RF semiconductor diode detectors [7], [8]. For the measurement, at least four devices are required - three detectors and a reference detector for sensing incident power [1]. The reflection coefficient is then computed by an appropriate method. Some of the methods could be found in [1], [9]. In our case, the equations from [10] were used

$$x = \frac{\sum_{i=1}^{4} F_i P_i}{\sum_{j=1}^{3} H_j P_j + P_4}, \tag{1}$$

$$y = \frac{\sum_{i=1}^{4} G_i P_i}{\sum_{j=1}^{3} H_j P_j + P_4} \tag{2}$$

where F, G, H are six-port parameters, $P_{1...4}$ are power readings from the detectors and $\Gamma = x + jy$ is reflection coefficient.

Multiport reflectometer uses additional probes which brings some improvement. In the case described in [11], additional probes help get higher accuracy. But in the case described in this paper and in [10], [12] and [13] the main aim of additional probes is to get higher bandwidth. This achieved arrangement can be considered as a cascade combination of simple six-ports, and classic six-port theory is applicable on this system. Since this system has more than the required number of outputs, the selection of a proper set has to be done.

Thus a suitable set of probes has to be selected at a proper stage during or before measurement at every discrete frequency. Afterwards common six-port calculation of measured or calibration data can be performed. The paper describes data processing method in six-port system which is modified to achieve larger bandwidth [10]. Other possibilities of extending bandwidth can be found in [14], [15]. Instead of the basic coupler which is used in six-port system, an improved coupler consisting of additional ports is used. The improved coupler can be called multiport [10]. In this case it is realized by transmission line with power detectors which are connected in several points.

2. System Design

Schematic diagram is presented in Fig. 1.

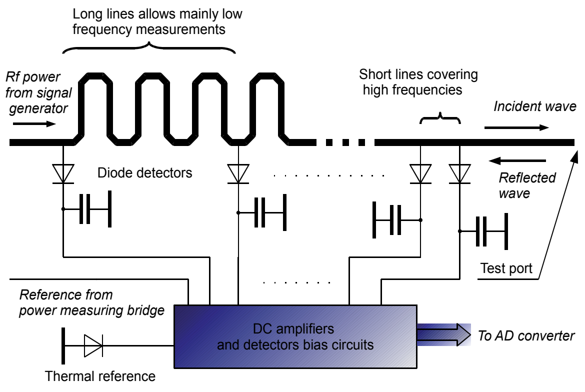

Fig. 1. Multiport reflectometer schematic diagram.

Multiport coupler [10] is designed to cover the whole intended bandwidth with a set consisting of minimally three detectors and one additional detector as a reference (see above). The first selection is done during the design of the multiport. It is based on assumption of the ideal transmission line (or with some losses and fluctuations depending on the model which is used) and leads to proper lengths of the line segments. Thus the multiport is formed by several transmission lines with different lengths. Another step of the design is to propose a "map" which assigns different sets of detectors to different frequency bands of measurement.

Nevertheless the assigning map does not consider non-idealities (mainly finite coupling factor of the detectors). Due to this fact the map is not suitable for using in calibration and measurement calculations. The suitable data for the assigning map has to be obtained by measurement on the real multiport device.

3. Six-port Selection in Multiport System

There are several possibilities how to process the output data of the detectors in the multiport system. As mentioned before, standard six-port calculation can be used. Specific number of sets of four detectors has to be selected before calibration or during measurement.

If the selection before calibration is performed, a reduction of saving data volume and computing time save can be achieved.

Alternatively, results for every possible set can be calculated without a selection. Then a set of preliminary results is obtained. The final result can be found by statistical method such as averaging or median.

3.1 Six-Port Selection before Calibration

Before any six-port calculation can be processed, a suitable set of the detectors has to be chosen. It is performed before calculation of the six-port calibration constants and can use some data from calibration measurement. This process uses a few different loads (two or three). Thus extra loads and measurement are not required. This method deals with selection of suitable set of detectors before any calibration calculations (obtaining six-port characteristic parameters) is performed. It is simple prediction.

The well known condition should be observed, that the phase difference between points where probes are located should be in a usable limit. This limit is determined mainly by overall uncertainty of power measurement in measuring system. The sufficient phase difference range can be defined as

$$30° \approx \alpha_{\min} < \alpha_p \tag{3}$$

where $\alpha_{\min}$ is minimum phase difference for acceptable accuracy, its practical value is about 30°.

If the selected set of the detectors will not fulfill this condition, power values are close to each other. As a result solution to (1), (2) can be ill-conditioned.

The main aim of the described algorithm is to find the set of detectors which fulfills the condition. For matched load the power readings P_1 to P_n will be almost the same in all cases. Then for reflective load, there should be set of detectors with different values $P_1 \neq P_2 \neq P_3$. An example of the situation can be seen in Fig. 2 (for 8 detectors).

The equations

$$2\pi \frac{l_n}{\lambda_l} + \theta_L = \frac{\pi}{2} + k\pi\,, \tag{4}$$

$$\alpha_n + \theta_L = \frac{\pi}{2} + k\pi \tag{5}$$

describe phase of standing wave on the measuring line when the detector is in the minimum of voltage. $|\Gamma_L| e^{j\theta_L}$ is reflection coefficient of the load, λ_l is wavelength on the line and l_n is distance from the test port.

Theoretical response can be solved. When the frequency sweep is done, the electrical distance between every detector and test port can be solved. Minimums in detector response can be found and then length can be solved from (4) or phase shift can be determined from (5). Once these phase shifts are given, proper sets of detectors fulfilling the condition (3) can be easily found.

In the prototype the selection by P_1, P_2, P_3 readings change with load seems to be usable. Unsuitable sets will have responses too close to each other. The suitable set gives different power readings when load is changed. The set of detectors with the highest difference d was used for next processing in the test case

$$d = \sum_{k=1}^{3} \left| P_{k,1} - P_{k,2} \right| + \sum_{o=1}^{2} \sum_{m=1}^{2} \left| P_{m,o} - P_{m+1,o} \right| \tag{6}$$

where $P_{k,1}$, $P_{k,2}$ is power value measured with load 1 or load 2, respectively, connected to test-port. Power readings were firstly normalized to the greatest of them. The first term describing the difference between responses of the same detector, but a different load, has maximum for maximum sensitivity on load change, the second term is the sum of differences of the different detectors, but for the same load, and gives minimum, when the detectors are close to each other. The second term effectively eliminates invalid six-port, while by using the first term the six-port with the best sensitivity to load change is selected.

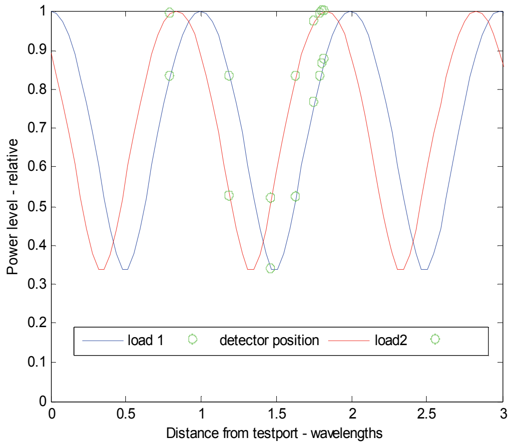

Fig. 2. An example of the situation in multiport based system, when a reflective load is connected to the test port.

The main advantage of the algorithm is that this process brings a high reduction of data. There is number of possible detector combinations, given by

$$N_D = \frac{q!}{k!(q-k)!} \tag{7}$$

where $k = 3$ is the number of detectors in one set (3 + reference), q is the number of detectors in the multiport system (without reference), N_D is the number of detector sets. By using this method, only one of them is selected and used at each frequency.

For example: the system with eight detectors (usable in band 10 MHz to 6 GHz) has 56 possible combinations of detectors sets according to (7). If 1 000 frequency steps are required, 56 000 calibration sets of eleven six-port parameters are obtained by using the next two methods (616 000 values). Nevertheless this algorithm produces only one number - one set of detectors on each frequency step. Thus calibration calculation is performed only one time for each discrete frequency and then only 1 000 sets of six-port parameters are obtained. In the most of the cases there can be found higher number of valid sets of detectors which fulfill (3), however only one such set is used. The rest of the sets are lost thus there is no way how to use them to get more accurate results.

This method is suitable for complex calibration processes, such as the robust method described in [16], because the saved machine time is considerable.

3.2 Six-Port Selection after Calibration

Another way how to get proper results for the whole bandwidth is to calibrate all possible sets of detectors. That means it will calculate sets of the calibration constants for all possible six-port combinations. Then measurement process produces values of reflection coefficient for every set of detectors – preliminary results. The selection of the best one (or more) had to be done.

Since six-port computations are working according to (1), (2), calibration process leads to set of matrixes

$$\begin{vmatrix} P_{11n} \cdots & P_{41n} & -x_{1n}P_{11n} \cdots & -x_{3n}P_{31n} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ P_{17n} \cdots & P_{47n} & -x_{1n}P_{17n} \cdots & -x_{3n}P_{37n} \end{vmatrix} \begin{vmatrix} F_{1n} \\ \vdots \\ \vdots \\ H_{3n} \end{vmatrix} = \begin{vmatrix} x_{1n}P_{41n} \\ \vdots \\ \vdots \\ x_{1n}P_{47n} \end{vmatrix}, \tag{8}$$

$$\begin{vmatrix} P_{11n} \cdots & P_{41n} & -y_{1n}P_{11n} \cdots & -y_{3n}P_{31n} \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ P_{17n} \cdots & P_{47n} & -y_{1n}P_{17n} \cdots & -y_{3n}P_{37n} \end{vmatrix} \begin{vmatrix} G_{1n} \\ \vdots \\ \vdots \\ H_{3n} \end{vmatrix} = \begin{vmatrix} y_{1n}P_{41n} \\ \vdots \\ \vdots \\ y_{1n}P_{47n} \end{vmatrix} \tag{9}$$

where $P_{a,b,n}$ are power readings from detectors a (1-4) for load b (1-7) connected to the test port in frequency n. $\Gamma_{b,n} = x + jy$ is the known reflection coefficient for calibration load b, for frequency n. $F_{c,n}$, $G_{c,n}$, $H_{d,n}$ are six-port parameters corresponding to each frequency n.

These matrix equations should be computed N_D times during each discrete frequency n.

Note that in tested sample the six-port calibration process uses the method with 7 standards from [10], but these processes are essentially applicable with an arbitrary calibration method.

For some combinations of detectors the matrixes (8), (9) can be singular and the calculation process fails. This indicates invalid and unusable six-port combinations at corresponding frequency.

Once calibration constants are obtained, they can be used in measurement process to obtain sets of values of the reflection coefficient Γ_{Ln}. In the ideal case, these should be identical $\Gamma_{L1} = \Gamma_{L2} =$... But in a real situation, these values are affected with different errors and $\Gamma_{L1} \neq \Gamma_{L2} \neq$ ... Then various statistical methods may be used to obtain (select) the result which is closest to true (unknown) value of Γ_L. There are some frequencies where only few of the preliminary results can be inaccurate however in some cases the most of the partial results are inaccurate and unusable.

The simplest way is calculating an average from all the preliminary results. But several values can be far from the right one. Then the average value will be inaccurate.

The median value calculated from the partial results gives better results than averaging. Values are sorted by their module and the mid-point value is picked from these sorted values.

4. Measurement Results

Multiport prototype system was realized and different described processing methods of partial results were compared. In Fig. 3 the block diagram of the measuring network can be seen. The measurement set up consists of a signal generator, a multiport coupler with detectors, a multichannel DC amplifier, and a multichannel ADC converter with a controller and an interface and network is controlled by PC. The reference measurement was made with the commercial network analyzer Agilent E8364B for comparison.

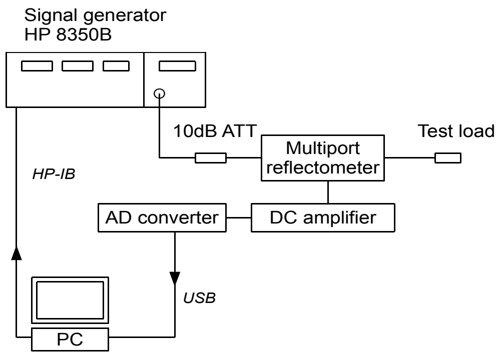

Fig. 3. Block diagram of the measuring system.

The fastest method was described in section 3.1. In the test case maximum difference between detectors response for two different loads was searched. As measurement has shown, the results are not very sensitive to the used loads. Only two different loads are required for covering the whole bandwidth. There loads with not too large difference in the reflection coefficient should be used. There is no possibility to average values of several sets to improve accuracy what results in higher fluctuations in of the measurement (Fig. 4). Nevertheless this can be solved by simple improvement which is realized by using three suitable values which were found. Data reduction is still high (3:56), and the result is more accurate (Fig. 5).

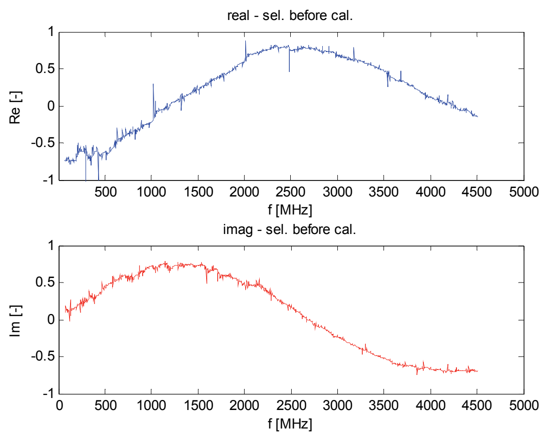

Fig. 4. Measurement result: selecting one six-port before calibration inductive lossy load, connected to the test port.

The second tested processing method was simple averaging of all partial results from all possible six-ports. It can be done during measurement and it needs all calibration data as was described above. Unfortunately, measurement has shown that this method totally failed (Fig. 6). It was caused by extreme values from six-port calculations where the calculation failed with invalid set of detectors.

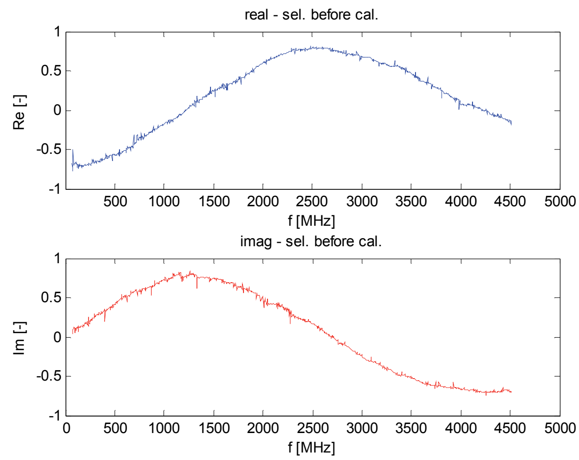

Fig. 5. Selecting three values before calibration (see text) - inductive lossy load, connected to the test port.

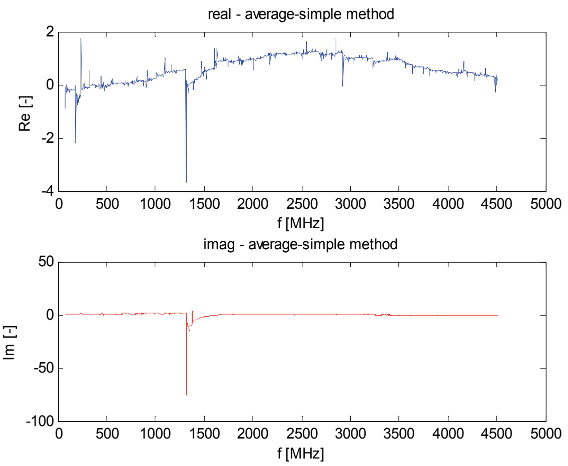

Fig. 6. Processing by using simple average from all partial results totally fails - inductive lossy load, connected to the test port.

The method had to be modified to get better results. All partial values were sorted by deviation from the average computed from all preliminary results and specific number (sufficient number is 5) with the highest deviations is omitted. This will eliminate sets of detectors which give preliminary results with the highest error. Measurement has shown, that after this improvement the method produces results comparable with median based method (which will be discussed bellow) as could be seen in Fig. 7. In Fig. 8 the dependence of final amplitude error (10) on the number of unused values is seen.

The difference between the value measured by the multiport reflectometer and the value from the reference measurement was calculated from:

$$\Delta = \sqrt{\left(x_M - x_T\right)^2 + \left(y_M - y_T\right)^2} \qquad (10)$$

where $\Gamma_M = x_M + jy_M$ is the measured reflection coefficient, and $\Gamma_T = x_T + jy_T$ is the reference measurement.

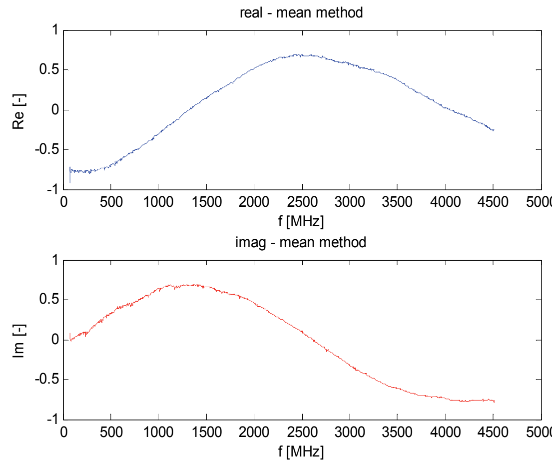

Fig. 7. Simple improvement produces better results - inductive lossy load, connected to the test port.

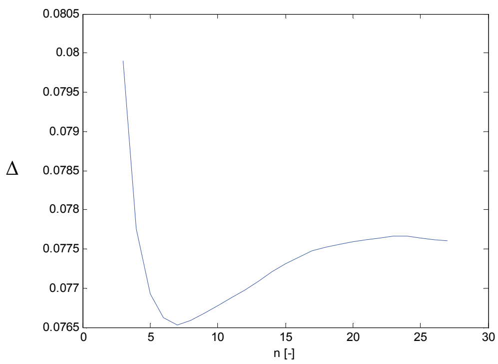

Fig. 8. Average – distance Δ (10) versus number of unused values.

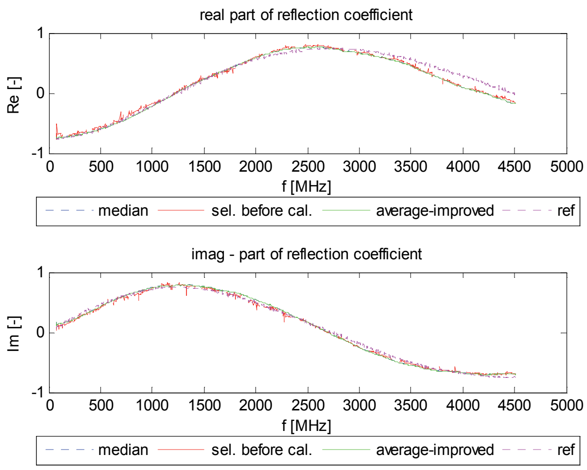

Fig. 9. Measurement result - inductive lossy load, connected to the test port, processed by using median from output values.

The last tested method of partial result processing was application of median function. It requires only one result from all. It worked approximately as well as "improved average" which was slightly better (Fig. 9).

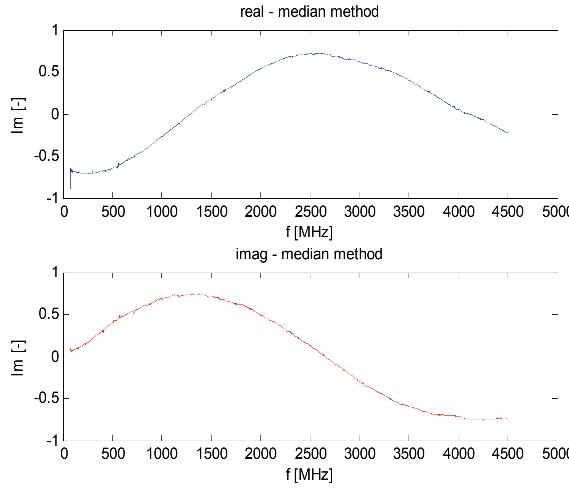

Fig. 10. Comparison between processing with using median, average and selection before calibration.

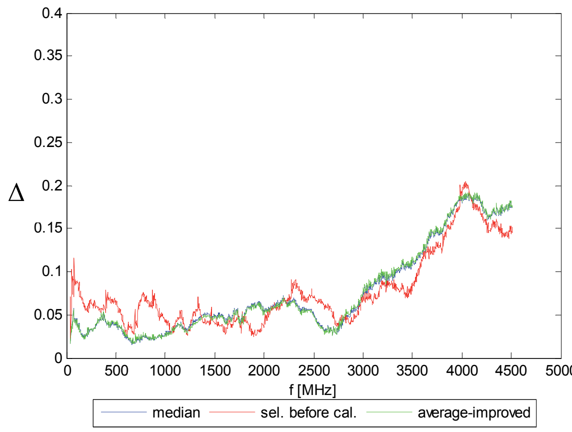

Fig. 11. Distance Δ between Γ_M and Γ_T vs. frequency

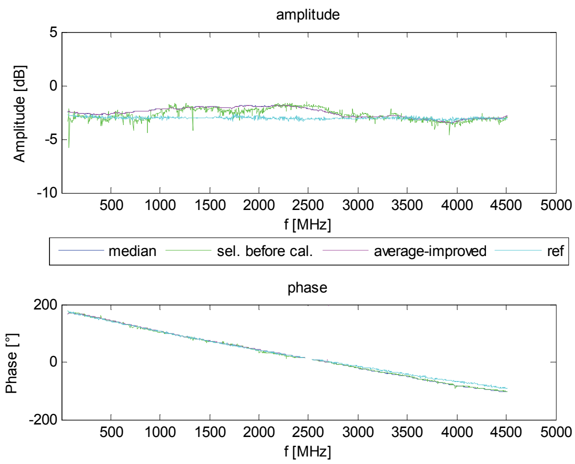

Fig. 12. Amplitude and phase measured and computed by using the described methods.

Comparison of all results of measurements is presented in Fig. 10. It shows real and imaginary parts of the reflection coefficient as obtained from six-port equations (1), (2). Calculated values of error (10) are in Fig. 11. Fig. 12 illustrates the measurement in terms of magnitude and phase.

5. Conclusions

Three basic methods of multiport data processing were tested and compared. Each method has its own advantages.

The valid set of the detectors can be selected before start of calibration process. This solution brings high data reduction and saves computing time. It is well suitable for real-time working systems. Fast response of the system can be achieved.

Simpler method, based on averaging, can be used as well. It requires selecting proper sets of detectors from all possible combinations after measurement and six-port calculations are made. Selected numbers of the results which are the closest to each other are then averaged. Specific optimum of the number of used values exists.

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