Matlab/Simulink Implementation of Wave-based Models for Microstrip Structures utilizing Short-circuited and Opened Stubs

Biljana P. Stošić, Darko I. Krstić, and Jugoslav J. Joković

Abstract—This paper describes modeling and analyzing procedures for microstrip filters based on use of one-dimensional wave digital approach. Different filter structures are observed. One filter is based on quarter-wave length short-circuited stubs and connecting transmission lines. The other one is based on cross-junction opened stubs. Frequency responses are obtained by direct analysis of the block-based networks formed in Simulink toolbox of MATLAB environment. This wave-based method allows an accurate and efficient analysis of different microwave structures.

Index Terms—Microstrip filters, microwave circuits, wave digital approach, block-based models.

I. INTRODUCTION

THE concepts of wave digital networks (WDNs) have their origins in the field of filter design, where they are designated more specifically as wave digital filters [1] – [4]. Generally speaking, WDNs can be viewed as a powerful modeling and analysis tool, as shown in [5] - [9].

In microwave structures, different junctions with several arms (i.e. of several transmission lines) are often employed. This paper outlines the concept of WDN and its use for the modeling and analysis of microstrip circuits which contain junctions with three and four arms. The special contribution is that it develops a global algorithmic view to WDN with respect to modeling and simulation purposes. Moreover, special emphasis has been put on a plain but concise presentation of the underlying ideas in order to address both readers with and without background in one-dimensional (1D) wave digital approach.

The paper is organized as follows. A brief review of 1D wave digital approach and a way of determining a minimal number of sections in WDN is described in Section 2. This modeling approach is critically dependent on precise determination of section numbers.

The wave digital models of a short-circuited transmission line and an opened line, which are presented in Section 3, represent the background to the modeling strategy that follow.

The WDN of the observed structures are given in Sections 4 and 5. They can be formed directly in the Simulink toolbox of MATLAB environment. In Section 6, block-based wave digital models of the structures are described. Response in WDNs can be found by use of formed block-diagram networks and some basic MATLAB functions.

Finally, a simulation validation of the proposed modeling and analysis approaches provided by means of a microstrip ultra-wideband filter utilizing short-circuited stubs and a low-pass filter of wide stop-band is presented and discussed in Section 7.

II. A BRIEF REVIEW OF WAVE DIGITAL APPROACH

Some general properties and the basic aspects of the 1D wave digital approach that are of considerable importance, related to this work, will be discussed here briefly. Generally speaking, the block-based 1D wave digital approach to analysis entails modeling structure as a network of interconnected blocks. WDNs containing adaptors are suitable for the modeling of a wide range of physical structures.

A lossless uniform transmission line is modeled by a two-port digital element with a delay occurring in the forward path. This wave digital two-port network is called the unit element (UE) [2]. The port resistances of the UE are equal and correspond to the characteristic impedance of uniform segment. The connection of two UE with different port resistances is achieved by two-port series/parallel adaptors [3].

A complex structure has to be divided into a cascade connection of uniform transmission lines (so-called uniform segments) where each segment is modeled by unit wave digital elements. In the complex microstrip structures, the delays of transmission lines vary from one another, and because of this each uniform segment has to be represented as a cascade connection of a certain number of UEs. The initial step in the

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proposed modeling methodology is to determine a minimal section numbers (i.e. number of cascaded UEs in uniform segments). This determination is based on the given relative error as shown below. An appropriate choice of a minimal section number in that model is very important because of the direct influence on the sampling frequency of that digital model, and on accuracy of the desired response.

A. Minimal Section Numbers [7]

A real delay T_Σ of a complex microstrip structure differs from the delay T_t of the WDN. In complex microstrip structures, delays of transmission lines are not multiple integers of the minimum delay. The number of sections n_k used for modeling an individual transmission line is found as the nearest integer of the ratio $q \cdot T_k / T_{min}$, i.e.

$$n_k = round\left[q \cdot T_k / T_{min}\right], \tag{1}$$

where $q \geq 1$ is a multiple factor, T_k is a delay on the kth transmission line, $T_{min} = min\{T_1, T_2, ..., T_M\}$ is a minimum delay, $k = 1, 2, ..., M$ and M is the number of uniform segments in the complex microstrip structure.

According to these data, the total delay for the digital model of the structure is

$$T_t = n_t \cdot T_{min} / q, \tag{2}$$

where the total number of UE in the WDN is

$$n_t = \sum_{i=1}^{M} n_k. \tag{3}$$

The relative error of a total delay in percentages is found as

$$er[\%] = \frac{T_\Sigma - T_t}{T_\Sigma} \cdot 100, \tag{4}$$

where

$$T_\Sigma = \sum_{k=1}^{M} T_k \tag{5}$$

is the sum of all transmission line delays, i.e. the total real delay of the structure, and T_t is given by (2).

The minimal number of sections needed for the modeling of the observed structure is found by using the relative error $n\_er[\%]$, which is already known. The procedure for determining the minimal number of sections with the error less than the given one can be done in a few steps. At the beginning, errors $er[\%]$ are found for different values of the multiple factor $q = 1, 2, ..., q_{max}$, where q_{max} is an arbitrary chosen value. Then, the first relative error with an absolute value less than the previously given error $|er[\%]| \leq n\_er[\%]$ is chosen. The number of sections for the kth transmission line n_k, $k = 1, 2, ..., M$, the total number of sections n_t, and the total delay of a digital model of the structure T_t, corresponding to that error are then used for modeling.

B. Sampling Frequency

The sampling frequency of the digital model of the planar structure is found for the chosen minimal number of sections, and is

$$F_s = 1 / T_s, \tag{6}$$

where

$$T_s = T_t / n_t \tag{7}$$

is the sampling period of the planar structure modeled by n_t sections. In order to match the response of the digital model with a real response, a new frequency is defined

$$F_{sm} = F_s / 2. \tag{8}$$

III. WAVE DIGITAL MODELS

A. Model of a Short-Circuited Transmission Line

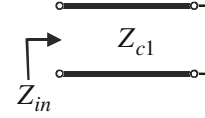Consider a short-circuited transmission line depicted in Fig.1.

Fig. 1. A short-circuited transmission line.

An input impedance of a lossles transmission line terminated by impedance Z_l has complex value

$$Z_{in} = Z_c \cdot \frac{Z_l + S \cdot Z_c}{Z_c + S \cdot Z_l}. \tag{9}$$

According to this equation and the fact that $Z_l = 0$ for a short-circuited, an input impedance of the line shown in Fig.1 is

$$Z_{in} = S \cdot Z_{c1}. \tag{10}$$

Billinear frequency transformation is

$$S = (1 - z^{-1}) / (1 + z^{-1}), \tag{11}$$

where $z = e^{ST}$ is a complex variable and $S = j\Omega$ is a normalized complex frequency.

By replacing the normalized complex frequency in the relation (10), the reflection coefficient is

$$\frac{B}{A} = \frac{Z_{in} - Z_{c1}}{Z_{in} + Z_{c1}} = -z^{-1}. \tag{12}$$

That means, the relation between the wave variables in frequency domain is

$$B = -z^{-1} \cdot A. \tag{13}$$

So, a short-circuited transmission line (Fig. 1) can be transform into wave digital network shown in Fig. 2 by using billinear transformation (11).
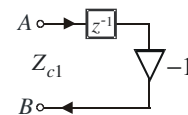

Fig. 2. Wave digital network of a short-circuited line.

B. Model of an Opened Transmission Line
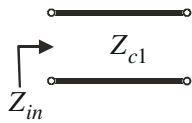
Consider an opened line depicted in Fig. 3.

Fig. 3. An opened transmission line.

According to equation (9) and the fact that $Z_c = Z_{c1}$ and load impedance $Z_l \to \infty$ for an opened circuit, an input impedance of the line shown in Figure 3 is

$$Z_{in} = Z_{c1} / S \,. \tag{14}$$

By replacing the normalized complex frequency in the relation (14), the reflection coefficient is

$$\frac{B}{A} = \frac{Z_{in} - Z_{c1}}{Z_{in} + Z_{c1}} = z^{-1} \,. \tag{15}$$

That means, the relation between the wave variables in frequency domain is

$$B = z^{-1} \cdot A \,. \tag{16}$$

So, an opened transmission line (Fig. 3) can be transform into wave digital network shown in Fig. 4 by using billinear transformation.
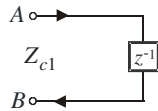

Fig. 4. Wave digital network of an opened line.

IV. WAVE DIGITAL NETWORK AS MODELING TOOL FOR STRUCTURE UTILIZING SHORT-CIRCUITED STUBS

Given is a microstrip structure, Fig. 5 [10]; it is assumed that this structure consists only of uniform segments where one segment is short-circuited stub. From such a structure an algorithmic model in the form of a wave digital network can be created, which is a rather complex reformulation where several constraints are to be met.

A wave digital network which corresponds to the observed segment connection is depicted in Fig. 6. The uniform segments have different characteristic impedances Z_{ck}, $k = 1,2,3$. All uniform segments are modeled by several cascaded UEs, short: $n_k \times T$ blocks.

These blocks, i.e. models of uniform segments UTL1, UTL2 and UTL3, are connected by use of one three-port parallel adaptor with port 2 being dependent. Adaptors are memoryless devices whose task is to perform transformations between pairs of wave variables that are referred to different levels of port resistance.

A parallel adaptor serves to interconnect, in parallel, n-ports with arbitrary port resistances $R_1, R_2,..., R_n$. A network of three-port parallel adaptor with port 2 being dependent is depicted in Fig. 7, [1-4]. The adaptor coefficients α_1 and α_2 are shown explicitly next to the ports 1 and 3, respectively. The coefficients are

$$\alpha_j = 2 \cdot G_j / (G_1 + G_2 + G_3), \qquad j = 1,2 \,, \tag{17}$$

where the port conductances are $G_k = 1 / Z_{ck}$, $k = 1,2,3$.

A series adaptor serves to interconnect, in series, n-ports with arbitrary port resistances $R_1, R_2,..., R_n$. In the symbolic representation of a two-port series adaptor [1-4] given in Fig. 8, it is shown explicitly the parameter α next to the port 1.
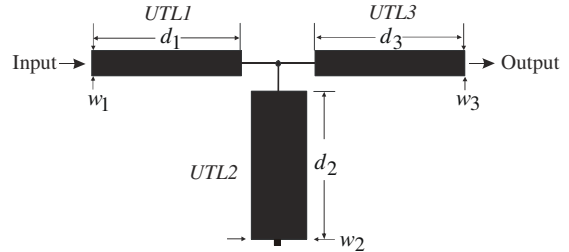

Fig. 5. Segment connection in microstrip structure.
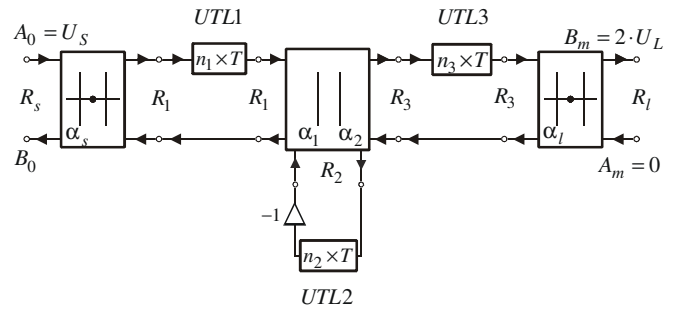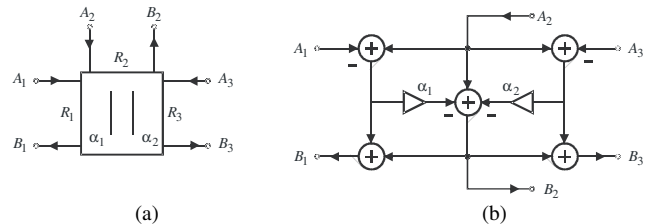

Fig. 6. WDN of the structure given in Fig. 5.

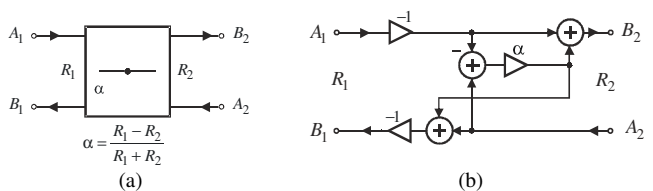Fig. 7. Three-port parallel adaptor with port 2 being dependent: (a) symbol, and (b) WDE.

Fig. 8. Two-port series adaptor: (a) symbol, and (b) WDE.

V. WAVE DIGITAL NETWORK AS MODELING TOOL FOR STRUCTURE WITH CROSS-JUNCTION OPENED STUBS

Another case of considerable interest is a circuit containing junction of four transmission lines. Given is a connection of segments in one microstrip structure with cross-junction opened stubs, Fig. 9; it is assumed that this structure consists only of uniform segments assigned from UTL1 to UTL4.
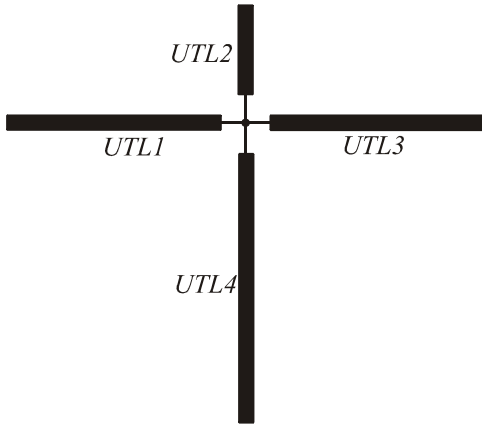
Fig. 9. Microstrip circuit: uniform segment connection.

It is easy to form an equivalent WDN of such structure, Figure 10, by proceeding according to the general method outlined in Section II. This figure illustrates a resultant network, i.e. structure model that consists of $n_t = \sum_{k=1}^{4} n_k$ UEs, one four-port parallel adaptor and two two-port series adaptors.
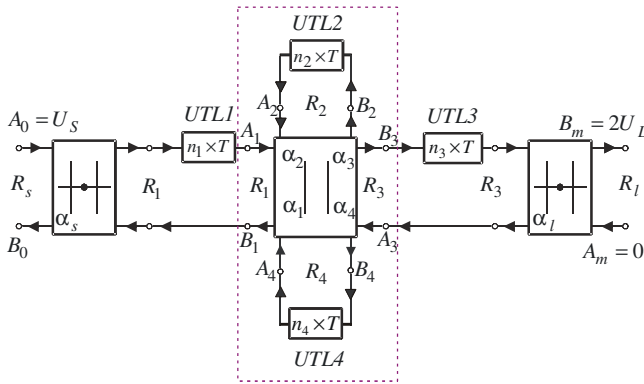

Fig. 10. Wave digital network of a planar microstrip structure with cross-junction opened stubs.

The equation set for four-port parallel adapter, symbolically given in Fig. 10, is:

$$B_k = (\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3 + \alpha_4 A_4) - A_k , \tag{18}$$

where the adaptor coefficients

$$\alpha_k = \frac{2G_k}{\sum_{j=1}^{n} G_j} , \ k = 1,2,3,4 , \tag{19}$$

depend on port conductances $G_k = 1/R_k$, with R_k being port resistances, and

$$\sum_{k=1}^{4} \alpha_k = 2 . \tag{20}$$

According to the last equation, it is possible to eliminate one coefficient in order to reduce number of adders in resultant wave digital network of this adaptor. In this case, the new equations are:

$$B_4 = A_4 - \sum_{k=1}^{3} \alpha_k (A_4 - A_k) , \tag{21}$$

$$B_k = B_4 + (A_4 - A_k) , \ k = 1,2,3 . \tag{22}$$

VI. MATLAB/Simulink Implementation of WDNs

In order to generate a method for construction of algorithm that efficiently implements microstrip structures utilizing short-circuited stubs or cross-junction opened stubs, their layouts have to be observed. A correct equivalent wave-based model depends on structure geometry.

MATLAB is an excellent tool for simulating structure, and for creating the valuable "proof of concept". Block diagram is a representation of physical structure using blocks. Individual blocks can be put together to represent the structure in block diagram form. Individual blocks can be the basic blocks or they can be subsystems. They are considered in the text given below.

The formed Simulink model of WDN in Fig. 6 is depicted in Fig. 11. The blocks **TLine_1**, **Stub_2** and **TLine_3** represent models of uniform segments. For these blocks, the Integer Delay blocks from Simulink/Discrete Library are used. The Integer Delay block delays its input by N sample periods. The block accepts one input and generates one output.

The blocks **ADP-S** and **ADP-L** represent two-port series adaptors, and block **ADP_T1S2T3** three-port adaptor. The two-port adaptors at the ends are used for matching source and load resistances to the rest of the WDN. The adaptor coefficients for the blocks **ADP-S** and **ADP-L** in the WDN are

$$\alpha_s = (R_s - Z_{c1})/(R_s + Z_{c1}) , \tag{23}$$
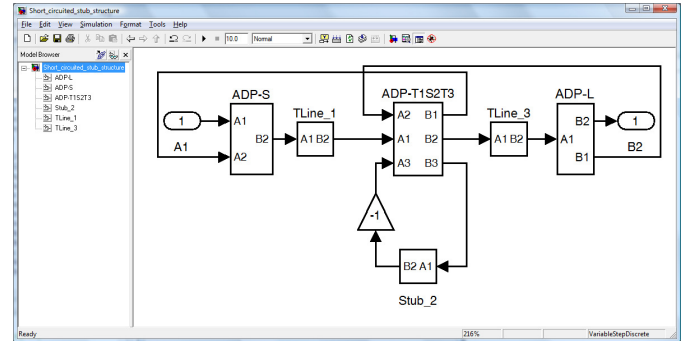
$$\alpha_l = (Z_{c3} - R_l)/(Z_{c3} + R_l) \cdot$$

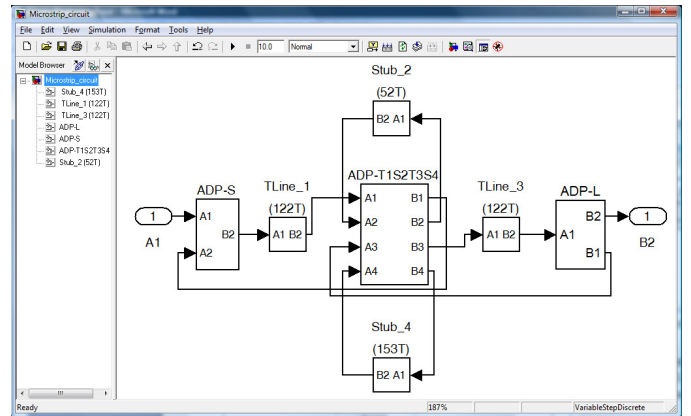Fig. 11. Simulink model of WDN given in Fig. 6.

Fig. 12. Simulink model of WDN from Fig. 10.

The formed Simulink model of WDN in Fig. 10 is depicted in Fig. 12. The blocks **TLine_1**, **Stub_2**, **TLine_3** and **Stub_4** represent models of uniform segments. Block **ADP_T1S2T3S4** represent four-port parallel adaptor.
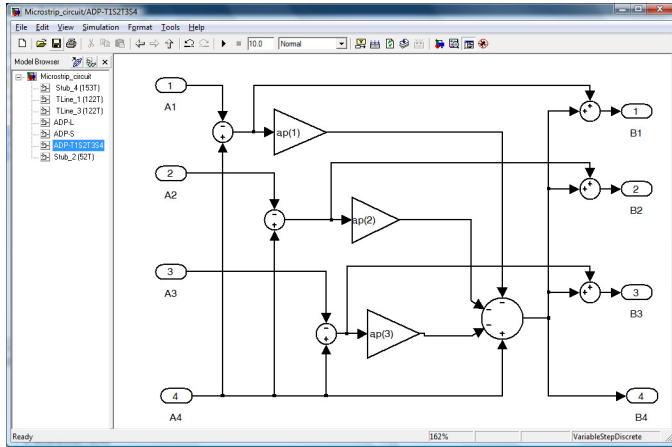

Fig. 13.   Simulink model of four-port parallel adaptor with port 4 being dependent.

According to relations (21) –(22), Simulink model of four-port parallel adaptor with port 4 being dependent, is depicted in Fig. 13.

A very simple method of analysis of the WDN is a block-diagram method. Each Simulink model represents a series of MATLAB and Simulink commands and functions which are used for its creation. Response is obtained directly in the time domain, and Fourier transformation is used for frequency response calculation. A major part here is formed Simulink model (mdl-file), whereby the mdl-file is run by m-file that is provided for initialization, response calculation and plotting, Fig. 14.
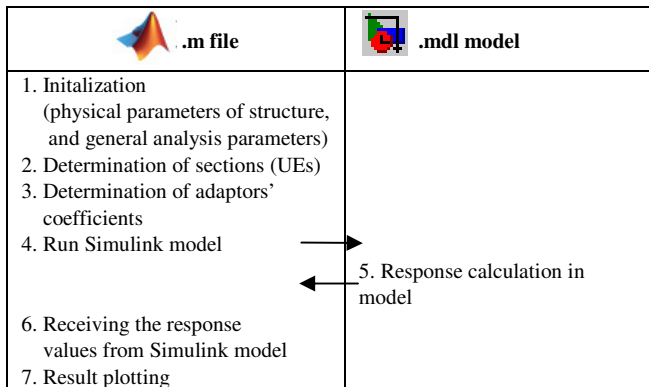

Fig. 14.   Algotihm for the implementation of WDN.

MATLAB built-in functions *dlinmod.m*, *dimpulse.m* and *fft.m* are employed to find a response of observed WDN. *Dlinmod.m* function obtains linear model from discrete system described by block-diagram. *Dimpulse.m* function gives impulse response of discrete-time linear systems. Function *fft.m* is the discrete Fourier transform, i.e. it gives response in the frequency domain.

VII.   APPROACH VERIFICATION

A.   A filter with short-circuited stubs

To demonstrate the main idea and approach, a microstrip ultra-wideband filter with a central frequency of $2.1\ GHz$ [10], [11] is depicted. The filter is based on quarter-wave length short-circuited stubs and connecting transmission lines. The layout is shown in Fig. 15. It is analyzed on FR-4 substrate with dielectric constant $\varepsilon_r = 4.6$, and the board thickness $h = 0.6\ mm$. Metallization is cooper and the metal thickness is $t = 17.5\ \mu m$. Simulink model of WDN for filter is depicted in Fig. 16.
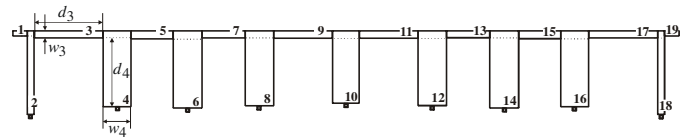

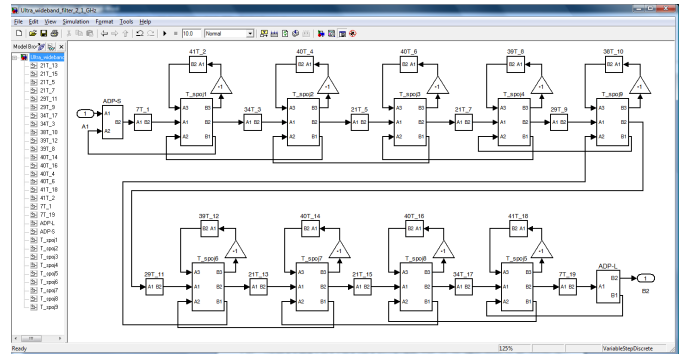Fig. 15. Layout of ultra wide-band filter with short-circuited stubs.

Fig. 16. Simulink model of the filter.

TABLE I

SEGMENT PARAMETERS

n	d [mm]	w [mm]	Zc [Ohm]	T [ps]
1,19	3.1000	1.1000	49.5082	19.2338
2,18	18.0000	1.5000	40.9808	113.1258
3,17	14.8000	1.5000	40.9808	93.0145
4,16	16.3000	6.0000	14.3797	108.8778
5,15	9.0000	1.7000	37.7671	56.8691
6,14	16.6000	6.2000	13.9839	111.0299
7,13	9.3000	1.5000	40.9808	58.4483
8,12	16.1000	6.1000	14.1790	107.6145
9,11	12.6000	1.6000	39.3056	79.4078
10	15.6000	5.7000	15.0181	103.9822

The filter is approximated by connection of 19 uniform segments with parameters given in the Table I. For given error of $n\_er = 0.01\%$, a total minimal number of sections in *WDN* is $n_t = 582$. The numbers of sections in individual segments n_k are 7, 41, 34, 40, 21, 40, 21, 39, 29, 38, 29, 39, 21, 40, 21, 40, 34, 41, and 7, respectively. A total delay for the digital model of the structure is $T_t = 1599.1561\ ps$, a multiple factor

is $q = 7$ and a minimum delay is $T_{\min} = 19.2338\,ps$. A total real delay of the structure is $T_{\Sigma} = 1599.2257\,ps$. A sampling frequency of the digital model of the planar structure for the chosen minimal number of sections is $F_s = 363.9420\,GHz$. In this case, a relative error of delay is $er = 0.004352\,\%$. According to relation (17), the three-port adaptor coefficients are: $\alpha_1 = \alpha_{18} = 0.5855$, $\alpha_2 = \alpha_{17} = 0.7073$, $\alpha_3 = \alpha_{16} = 0.4053$, $\alpha_4 = \alpha_{15} = 0.4398$, $\alpha_5 = \alpha_{14} = 0.4327$, $\alpha_6 = \alpha_{13} = 0.3988$, $\alpha_7 = \alpha_{12} = 0.4054$, $\alpha_8 = \alpha_{11} = 0.4227$, $\alpha_9 = \alpha_{10} = 0.4332$. The two-port adaptor coefficients, relation (23), are $\alpha_S = -\alpha_L = 0.004942$.

The results obtained by direct analysis of WDN, and by simulations (linear and momentum) in ADS (Advanced Design System) [12], are depicted in Fig. 17. It can be concluded that WDN and ADS curves show a good agreement in whole frequency range.
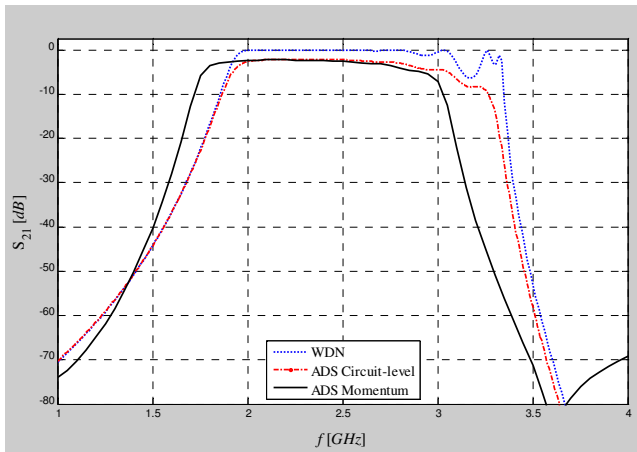

Fig. 17. Frequency response comparison.

B. Structure with cross-junction opened stubs – A simple microstrip circuit

The layout of a structure with cross-junction opened stubs is shown in Fig. 18. It is analyzed on substrate with dielectric constant $\varepsilon_r = 2.2$, and the board thickness $h = 3.175\,mm$. The filter is symmetrical and approximated by connection of 4 uniform segments with parameters given in the Tables II and III. Simulink model of WDN for this structure is depicted in Fig. 12.

For given error of $n\_er = 0.01\,\%$, a total minimal number of sections in WDN is $n_t = 449$. The numbers of sections in individual segments n_k are 122, 52, 122, and 153, respectively. A total delay for the digital model of the structure is $T_t = 2521.9705\,ps$ where a multiple factor is $q = 52$ and a minimum delay is $T_{\min} = 292.0507\,ps$. A total real delay of the structure is $T_{\Sigma} = 2521.7453\,ps$. A sampling frequency of the digital model of the planar structure for the chosen minimal number of sections is $F_s = 178.0513\,GHz$. In this case, a

relative error of delay is $er = 0.0089\,\%$. According to the relation (22), the four-port adaptor coefficients are $\alpha_1 = \alpha_2 = \alpha_3 = 0.5$. The two-port adaptor coefficients are $\alpha_S = -\alpha_L = -0.002894$.
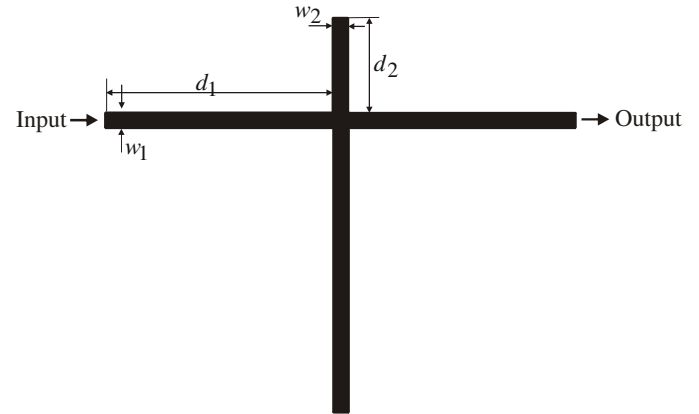

Fig. 18. Layout of a microstrip circuit with cross-junction opened stubs.

TABLE II

PARAMETERS OF UNIFORM SEGMENTS

WITHOUT ANY DISCONTINUITIY EFFECTS

nLine	d [mm]	w [mm]	Zc [Ohm]	T[ps]
1	150.0000	9.7800	50.2902	683.9538
2	62.5000	9.7800	50.2902	284.9808
3	150.0000	9.7800	50.2902	683.9538
4	187.5000	9.7800	50.2902	854.9423

TABLE III

PARAMETERS OF UNIFORM SEGMENTS

WITH EFFECTS OF OPENED STUBS

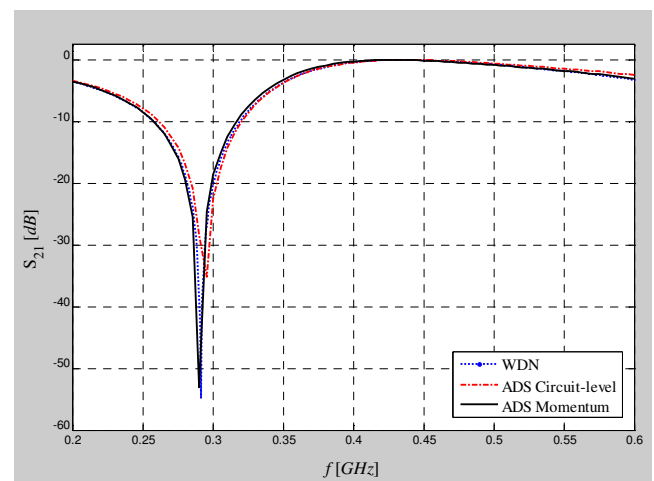| nLine	d [mm]	w [mm]	Zc [Ohm]	T [ps]
1	150.0000	9.7800	50.2902	683.9538
2	64.0505	9.7800	50.2902	292.0507
3	150.0000	9.7800	50.2902	683.9538
4	189.0505	9.7800	50.2902	862.0122

Fig. 19. Microstrip resonator utilizing opened stubs: amplitude-frequency response of S_{21} parameter.

Fig. 19 shows amplitude-frequency responses of S_{21} parameter both simulated in MATLAB by a new proposed approach and obtained in ADS simulator (Advanced Design Software).

C. Structure with cross-junction opened stubs – Low-pass filter of wide stop-band

A novel microstrip structure for low-pass filter of wide stop-band with cross-junction opened stubs, which layout is shown in Fig. 20, is proposed by Liu *et al.* in [13]. The dielectric constant of material is $\varepsilon_r = 2.22$ with a thickness $h = 0.254\,mm$. As a wave digital approach to analysis entails modeling a microstrip structure as a network of interconnected blocks, this filter is approximated by connection of 10 uniform segments. ADS model of the filter is depicted in Fig. 22. Simulink model of WDN for this low-pass filter of wide stop-band is depicted in Fig. 23. Tables IV and V show the lengths and widths of uniform segments in the layout, before and after inclusion of open-end discontinuity effects.
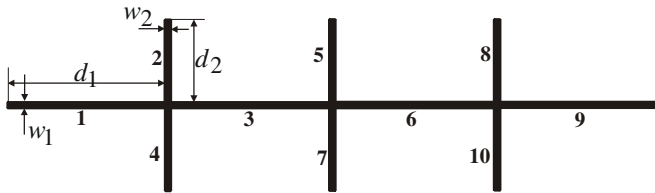

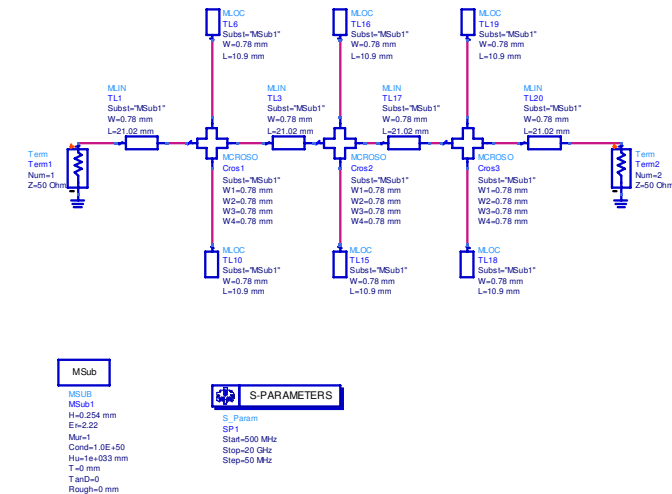Fig. 20. Layout of filter with cross-junction opened stubs.

Fig. 21. ADS circuit-based model of the filter with cross-junction opened stubs.
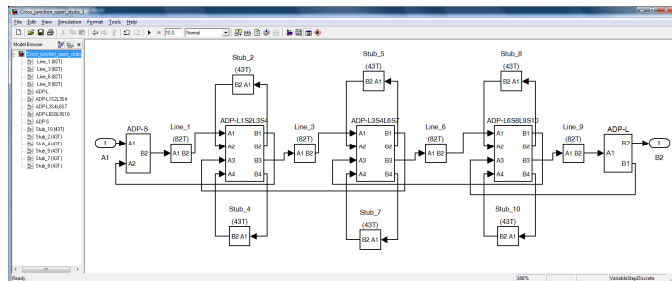

Fig. 22. Simulink model of low-pass filter.

TABLE IV
PARAMETERS OF UNIFORM SEGMENTS
WITHOUT ANY DISCONTINUITIY EFFECTS INCLUDED

nLine	d [mm]	w [mm]	Zc [Ohm]	T [ps]
1,3,6,9	21.0200	0.7800	50.2000	96.2073
2,4,5,7,8,10	10.9000	0.7800	50.2000	49.8886

TABLE V
PARAMETERS OF UNIFORM SEGMENTS
WITH INCLUDED EFFECTS OF OPENED STUBS

nLine	d [mm]	w [mm]	Zc [Ohm]	T [ps]
1,3,6,9	21.0200	0.7800	50.2000	96.2073
2,4,5,7,8,10	11.0237	0.7800	50.2000	50.4549

For given error of $n\_er = 0.01\%$, a total minimal number of sections in WDN is $n_t = 586$. The numbers of sections in individual segments n_k are 82, 43, 82, 43, 43, 82, 43, 43, 82, and 43, respectively. A total delay for the digital model of the structure is $T_t = 687.5584\,ps$ where a multiple factor is $q = 43$ and a minimum delay is $T_{min} = 50.4549\,ps$. A total real delay of the structure is $T_\Sigma = 687.5944\,ps$. A sampling frequency of the digital model of the planar structure for the chosen minimal number of sections is $F_s = 852.2466\,GHz$. In this case, a relative error of delay is $er = -0.0052\%$. According to the relation (22), the four-port adaptor coefficients are $\alpha_k = 0.5$, $k = 1,2,...,9$. The two-port adaptor coefficients are $\alpha_S = -\alpha_L = -0.001996$.

Amplitude-frequency responses of S_{21} parameter, both simulated in MATLAB by a new proposed approach and obtained in ADS simulator (Advanced Design Software), are shown in Figs. 23 and 24.
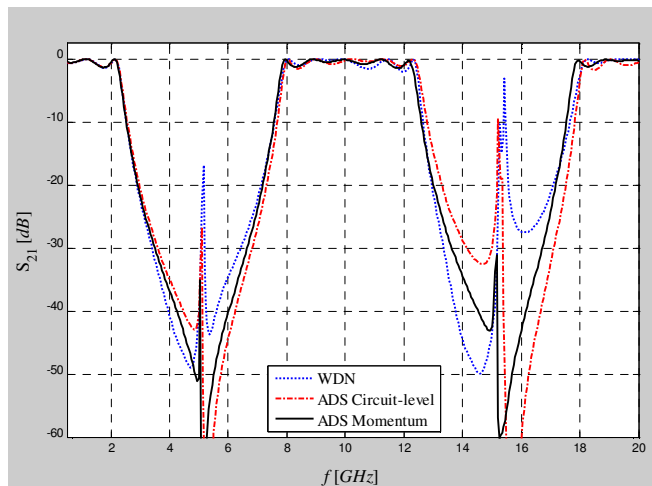

Fig. 23. Microstrip filter with cross-junction opened stubs: amplitude-frequency response of S_{21} parameter.
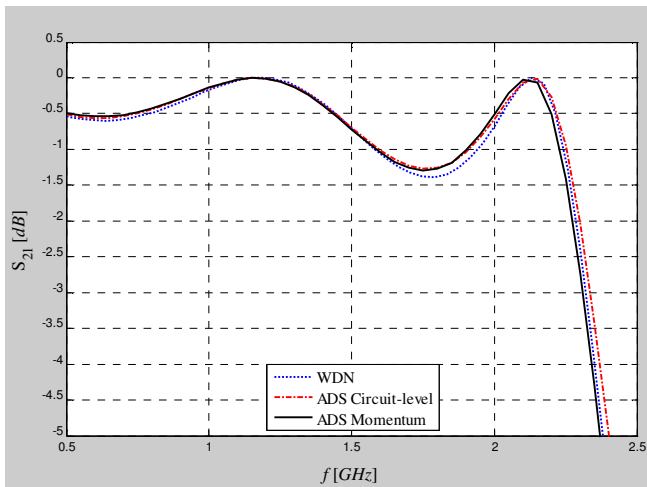
Fig. 24.   Microstrip filter with cross-junction opened stubs: amplitude-frequency response of S_{21} parameter in passband.

D. Result Discussion

The S_{21} parameter responses, shown in Figs. 17, 19, 23 and 24, are counted by analyzing WDNs in MATLAB as well as by using known software package ADS (Advanced Design System). The obtained results are similar in general. In all figures, the WDN results show a small differences in comparison with the results of Momentum (electromagnetic 2.5D MoM) simulation done in ADS. These differences can be from not exact modeling of discontinuities, as well as not including conductor and dielectric losses.

According to these findings, a simple wave-based models and their implementation in MATLAB/Simulink, can produce results that are similar to the much more sophisticated methods.

VIII. Conclusion

Recently, much work has concentrated on the development of wave digital approach for modeling and analysis of different physical systems. A detailed review of application of WDF structures for electromagnetic field simulation is given in [14] and [15]. After an extensive search in the literature it was found an application of ADS [12] to simulations of different microstrip structures based on their wave digital network representations [16]. In [17], a framework for the automated generation of the wave digital structures is presented, and the reference circuit is assumed to comprise arbitrary connection types.

In this paper, a framework for the generation of equivalent wave digital networks for planar microstrip structures has been presented. The concept of a generalized method which was established earlier for stepped-impedance structures and structures with opened stubs, is extended to another interesting problems with junction of several transmission lines.

This wave-based digital approach into MATLAB/Simulink enables an efficient and easy simulation of microstrip structures of different geometries. Also, allows the user to get the responses in both the frequency and time domains in short time intervals.

The broadband accuracy of the suggested procedures has been demonstrated in analyses of filters realized in the microstrip line technique.

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