High Accuracy Time Domain Modeling of Microstrip Discontinuities by Using Modified TDR Based on Barker Codes with Flat Spectrum and Integrated Side-Lobes

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Abstract **─** In this paper, a novel time domain method by using a modified time domain reflectometry is presented for high accuracy modeling of microstrip discontinuities. The ordinary stimulus signals used in the TDR technique are voltage step or voltage impulse. In this paper, we propose an alternative technique, whereby a modified excitation pulse based on Barker-Code orthogonal pulses is employed as the stimulus signal in TDR. The advantage conferred by "Barker codes TDR" is that more energy is available at higher frequencies in contrast with conventional step or impulse TDR, and so a higher bandwidth and higher accuracy of the line impedance is achieved. It can also be advantageous when the user is looking for precision in spatial localization, say in a connector or similar in-line structure, as the increased energy at higher frequencies can help. Simulated results are presented to validate the usefulness of the proposed method for calculating the precise amount of time-dependent equivalent circuit of microstrip discontinuity.

Index Terms **─** Finite difference time domain (FDTD), microstrip discontinuity, time domain reflectometry (TDR), and time domain modeling.

I. INTRODUCTION

Time domain reflectometry (TDR) is a well known technique that is typically used to measure the impedance of discontinuities as a function of time (or distance) in electronic systems [1-3]. A TDR instrument consists primarily of an oscilloscope and a test signal generator, where the test signal is traditionally a voltage step. As a consequence of the Fourier transform, the energy in the spectrum of a step falls as the frequency increases. On the other hand, an ideal impulse (Dirac delta) test signal has a theoretically flat bandwidth. Recent studies have demonstrated that step TDR can successfully be used to characterize the reflection scattering parameter S_{11} of antennas [4-6].

Several factors affect a TDR system's ability to resolve closely-spaced discontinuities. If a TDR system has insufficient resolution, small or closely-spaced discontinuities may be smoothed together into a single aberration in the waveform. This effect may not only obscure some discontinuities, but it also may lead to inaccurate impedance readings. Rise time, settling time, and pulse aberrations of the stimulus signal can also significantly affect a TDR system's resolution. Two neighboring discontinuities may be indistinguishable to the measurement instrument if the distance between them amounts to less than half the system rise time [2, 3]. Also, many factors contribute to the accuracy of a TDR results. These include the TDR system's step response, probe and interconnect reflections and DUT losses, step amplitude accuracy, baseline correction, and the accuracy of the reference impedance (ZO) used in the measurements. All TDR measurements are relative; they are made by comparing reflected amplitudes to incident amplitude.

In this paper, we explore the advantages of making modified impulse TDR results, similar to a traditional step TDR but employing a modified signal by using orthogonal codes instead of a step like or impulse like (Gaussian) signal. This allows us to compare theory with simulation. The

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motivation behind this work is driven by the fact that a TDR is less expensive than a vector network analyzer (VNA), but more importantly the time localization of the energy in the transient test signal means that the user can dispense with the anechoic chamber that is required for antenna measurements with a sine wave exciting signal. The advantage conferred by "Barker codes TDR" is that more energy is available at higher frequencies than with conventional step or impulse TDR, and so a higher bandwidth and higher accuracy of the line impedance is achieved. Simulated results are presented to validate the usefulness of the proposed method for calculating precise amount of time-dependent equivalent circuit of microstrip discontinuity.

II. FREQUENCY DOMAIN COMPARISON OF THE STIMULUS SIGNALS SPECTRUM

The unit impulse (Dirac delta) function is defined as having zero amplitude for all time except at $t = 0$, where it has infinite amplitude,

$$\delta(t) = \begin{cases} 0 & t \neq 0 \\ \infty & t = 0 \end{cases} . \quad (1)$$

The Fourier transform for the unit impulse is,

$$F[\delta(t)] = 1 . \quad (2)$$

In general the unit impulse is a theoretical construct and cannot physically exist [7], it is used as a limiting case for when the width of a pulse approaches zero. Derived from the convolution of two rectangular ("rect") functions, the trapezoid function provides an approximation of a realistic impulse with finite rise and fall times [7],

$$h(t) = \frac{1}{\tau} rect\left(\frac{t}{\tau}\right) \otimes A.rect\left(\frac{t}{T}\right) \quad (3)$$

in which A is the trapezoid amplitude, T is the full width at half maximum (FWHM), and τ is the rise/fall time from 0 % to 100 % of the amplitude. The Fourier transform of $h(t)$ is given by,

$$F[h(t)] = AT \sin c(f\tau) \sin c(fT). \quad (4)$$

The second order of the Barker-code functions is defined as,

$$B_2(t) = h(t+1) - h(t-1) . \quad (5)$$

The Fourier transform of $B_2(t)$ is given by,

$$F[B_2(t)] = (e^{-j2\pi f} - e^{j2\pi f}).AT \sin c(f\tau) \sin c(fT). \quad (6)$$

Generally, we can write the i^{th} order of the Barker-code stimulus signal as [8],

$$B_i(t) = \sum_{i=1}^{N} \beta_i . h(t + \alpha_i \tau) \quad (7)$$

where, β and α are the amplitude and the order of shifting in the Barker-codes sequence, respectively. Generally, Barker-codes are subsets of pseudo-noise (PN) sequences [8]. The origin of the name pseudo-noise is that the digital signal has an autocorrelation function, which is very similar to that of a white noise signal: Impulse like. PN sequence may also be periodic. Such sequences are known as Barker sequences. Barker-codes are commonly used for frame synchronization in digital communication systems. Barker-codes have a length of at most 13 and have low correlation side lobes. Barker sequences are too short to be of practical use for spectrum spreading. A correlation side lobe is the correlation of a code word with a time-shifted version of itself. The correlation side lobe, C_k for a k-symbol shift of an N-bit code sequence, $\{X_j\}$ is given by,

$$C_k = \sum_{j=1}^{N-k} X_j X_{j+k} \quad (8)$$

where, X_j is an individual code symbol taking values +1 and -1, for 0 < j < N, and the adjacent symbols are assumed to be zero. The Barker-code generator block provides the codes with various order listed in Table 1.

Table 1: Barker-codes for various orders.

Order (i)	Barker-Code (β_i)
1	[-1]
2	[-1 1]
3	[-1 -1 1]
4	[-1 -1 1 -1]
5	[-1 -1 -1 1 -1]
7	[-1 -1 -1 1 1 -1 1]
11	[-1 -1 -1 1 1 1 -1 1 1 -1 1]
13	[-1 -1 -1 -1 -1 1 1 -1 -1 1 -1 1 -1]

Figure 1 presents a number of stimulus signals with their spectra that will be compared with the spectrum of Barker-codes. It can be seen that even the realistic, limited Barker signal contains more energy than an ideal rectangular pulse. When the step waveform is not ideal, but similar to what is practically available today, the comparison becomes even more favorable, as can be seen in the same figure in [9]. Finally, as shown in Fig. 1, the Barker-codes with higher orders have a flat frequency response with integrated side-lobes [10].

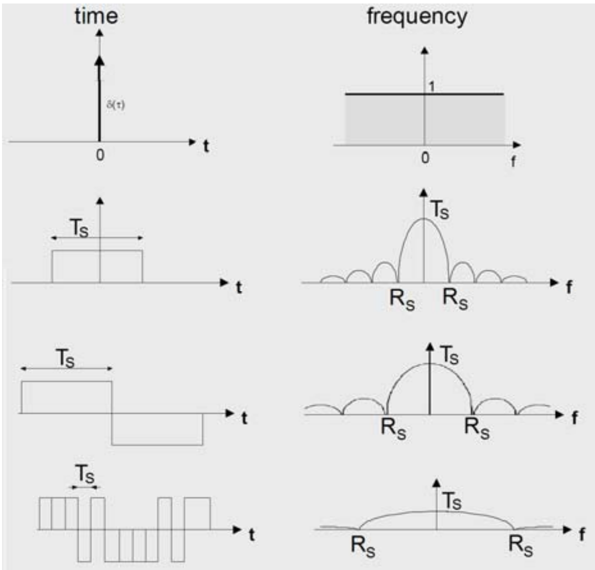

Fig. 1. An ideal unit impulse, rectangular pulse, and some practical Barker-codes of unit amplitude and its Fourier transform.

III. RESULTS AND SISCUSSIONS

This section describes the simulated line impedance of the microstrip discontinuity using the proposed Barker-codes TDR and compares it with the simulated line impedance obtained using the conventional step TDR and the equivalent circuit methods. In order to illustrate the proposed method performance, a step-like microstrip discontinuity with mentioned design parameters were simulated, and the TDR results of the input impedance for them in equivalent circuit and full-wave analysis cases are presented and discussed. The simulated full-wave TDR results are obtained using the Ansoft simulation software high-frequency structure simulator (HFSS) [11].

The proposed microstrip transmission line with step like discontinuity is shown in Fig. 2 (a), which is printed on an FR4 substrate of thickness 0.8 mm, permittivity 4.4, and loss tangent 0.018. This defected structure on the 50-Ω microstrip line will perturb the incident and return currents and induce a voltage difference on the microstrip line. These two effects can be modelled as a T-shaped LC circuit, as shown in Fig. 2 (b) [12]. The equivalent circuit parameters are defined as,

$$C = 0.00137h\frac{\sqrt{\varepsilon_{reff}}}{Z_{C1}}\left(1-\frac{W_2}{W_1}\right)\left(\frac{\varepsilon_{reff}+0.3}{\varepsilon_{reff}-0.258}\right)\left(\frac{W_1/h+0.264}{W_1/h+0.8}\right) \quad (9)$$

$$L_1 = \frac{L_{W1}}{L_{W1}+L_{W2}}L \text{ , and } L_2 = \frac{L_{W2}}{L_{W1}+L_{W2}}L$$

where,

$$L_{Wi} = Z_{Ci}\sqrt{\varepsilon_{reff}}\Big/c \text{ , and } L = 0.000987h\left(1-\frac{Z_{C1}}{Z_{C2}}\right)^2,$$

where L_{Wi} for i =1, 2 are the inductances per unit length of the appropriate microstrips, having widths W_1 and, W_2, respectively. Z_c and ε_{reff} denote the characteristic impedance and effective dielectric constant corresponding to width, and h is the substrate thickness in micrometres [12]. The optimal dimensions of the equivalent circuit model parameters for the proposed microstrip transmission line with step-like discontinuity are specified in Table 2.

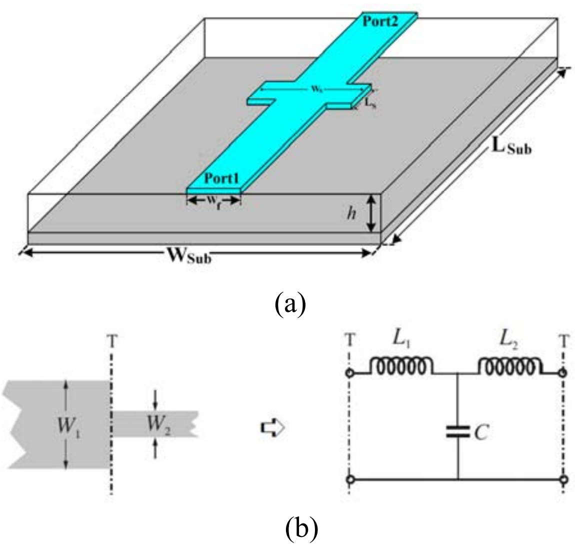

Fig. 2. (a) Geometry of the proposed microstrip transmission line with step-like discontinuity and (b) step-like microstrip discontinuity and its equivalent circuit model [12].

Table 2: The dimensions of proposed microstrip transmission line with step-like discontinuity.

Param.	mm	Param.	mm	Param.	mm
W_{Sub}	12	L_{Sub}	18	W_f	1.5
h	0.8	W_S	4	L_S	2

The equivalent circuit model parameters are listed in Table 3.

Table 3: Equivalent circuit model parameters.

Element	DGS
L_1	1.131 (nH)
C	1.181 (pF)
L_2	0.858 (nH)

The simulated TDR curves with different values of rise time and discontinuity distance from reference port (*d*) are plotted in Fig. 3. As shown in Fig. 3, when the distance between the reference port and the discontinuity location increases from 10 mm to 50 mm, the amount of the line impedance is varied from 33 Ω to 37.5 Ω. Also, as the rise time of the excitation signal increases from 20 psec to 30 psec, the port reflection over shoot is varied from 4 % to 7 %. From these results, we can conclude that the accuracy of discontinuity is varied by changing *d* and rise time [13]. Therefore, due to variation of the results in various conditions of distance and T_{rise}, to have an accurate judgment for the proposed method performance we need to plot TDR curves in a stable and constant condition for all of scenarios, as shown in Figs. 4 and 5.

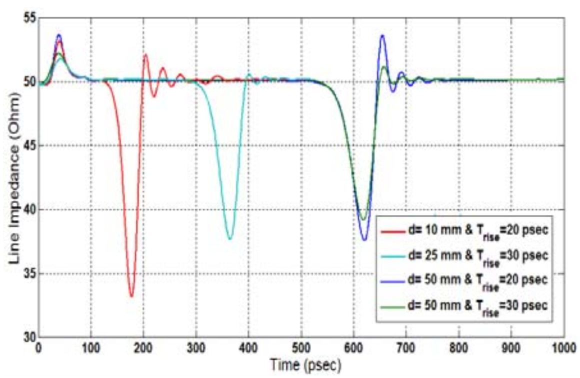

Fig. 3. Simulated TDR characteristic with different values of rise time (T_{rise}) and discontinuity distance from reference port (*d*).

Figure 4 shows the effects of T_{rise} with different values on the line impedance (TDR) in comparison with the ideal step for the proposed microstrip transmission line with step-like discontinuity. As shown in Fig. 4, these reports start, for t = 0.5 nsec, with an impedance just under 50 Ω. This is indeed the characteristic impedance of the microstrip line. At impedance discontinuities, part of the input signal is reflected. These reflections, after traveling back, reach terminal port 1 and are observed there [9]. From these observations, the characteristic impedances along the transmission line can be computed. As shown in Fig. 4, when the T_{rise} increases from zero in ideal step case to 30 psec, the line impedance in the center location of the step discontinuity is varied from 35 GHz to 38 GHz. From these results, we can conclude that the line impedance in the discontinuity location is controllable by changing the T_{rise}. In order to decrease the discrepancy between the simulated TDR data and the ideal step result and also to achieve the accurate impedance characteristics for the designed discontinuity, we need a stimulus signal with lower T_{rise}.

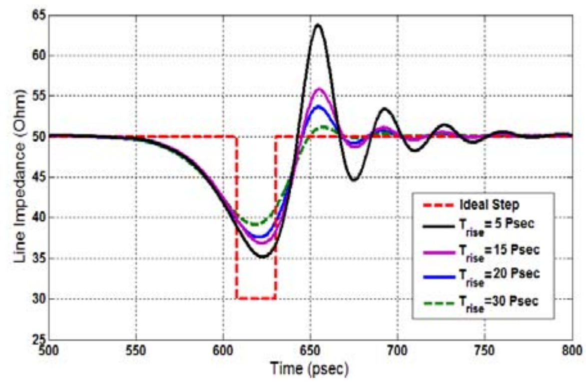

Fig. 4. Time dependent impedance with incident pulse having different rise time when a 1 mm step is inserted.

To improve the accuracy of the TDR results, without decreasing T_{rise}, Fig. 5 shows the simulated reflection waveform observed at port 1 of the defected structures, with a 50 Ω termination at port 2. The excitation source is a step wave with amplitude of 1 V and rise time of 20 psec. The TDR results for the equivalent circuit with C = 1.181 pF, L_1 = 1.131 nH, and L_2 = 0.858 nH based on the method described in [4] and specified in Table 1 are also shown for comparison. The corresponding results generated by Barker-codes TDR are also shown in this figure. Two cases are studied for Barker-codes TDR, with different code length. It is clearly shown that our TDR results with modified excitation signal by Barker-codes gives a very good accuracy, and the error is less than 1 % in this case in our simulation. It is apparent from this figure that the energy in the modified TDR reflection exceeds the energy in the step TDR reflection. Therefore, the modified Barker-codes TDR results follows the transmission line reference more closely than does the ordinary step TDR results.

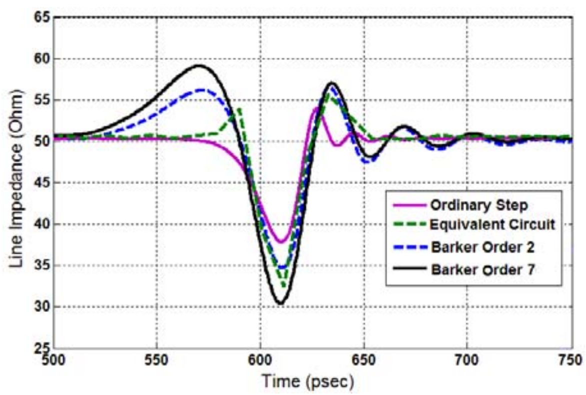

Fig. 5. The reflected waveforms comparison for simulated results by HFSS, equivalent circuit model, and two cases of Barker-codes for the proposed defected microstrip structure shown in Fig. 2 (a).

IV. CONCLUSION

Time domain reflectometry (TDR) with finite difference time domain (FDTD) method analysis is a novel technique that is typically used to calculate the time modeling of a microstrip structure. To improve the accuracy of the TDR results, without decreasing T_{rise}, we proposed an alternative technique, whereby a modified excitation pulse based on Barker-code orthogonal pulses is employed instead of the stimulus signal in TDR. It can also be advantageous when the user is looking for precision in spatial localization, say in a connector or similar in-line structure, as the increased energy at higher frequencies can help. The simulated results showed good agreement with the numerical prediction.

REFERENCES

[1] R. Tamas, G. Caruntu, and D. Popa, “A time-domain measuring technique for ultra-wide band antennas,” *Microwave and Optical Technology Letters*, vol. 53, no. 2, pp. 281-286, Feb. 2011.

[2] *Time Domain Reflectometry Theory*, Agilent Technologies, USA, Application Note 1304-2, 2006.

[3] A. Cataldo, G. Monti, E. De Benedetto, G. Cannazza, L. Tarricone, and L. Catarinucci, “Assessment of a TD-based method for characterization of antennas,” *IEEE Trans. Instrum. Meas.*, vol. 58, no. 5, pp. 1412-1419, May 2009.

[4] M. Ojaroudi and E. Mehrshahi, “Novel band-stop small square monopole antenna by using interdigital strip protruded inside the recangular slot as a band-stop filter with its equivalen circuit based in TDR analysis for UWB applications,” *International Symposium on Antennas and Propagation* , ISAP 2012, NAGOYA – JAPAN, 2012.

[5] C. Chiu, W. Chen, K. Liao, B. Chen, Y. Teng, G. Huang, and L.Wu, “Pad characterization for CMOS technology using time domain reflectometry,” *in Proc. IEEE Int. RF and Microwave Conf.*, in Kuala Lumpur, pp. 215-217, Dec. 2008.

[6] M. Harper, N. Ridler, and M. Salter, “Comparison between root-impulse-energy and vector network analyzer methods for measuring loss on printed circuit boards,” *in ARFTG Microwave Measurement Symp.*, in Portland, OR, pp. 20-25, 2008.

[7] M. Kowalski, “A simple and efficient computational approach to chafed cable time-domain reflectometry signature prediction,” *25th Annual Review of Progress in Applied Computational Electromagnetics (ACES)*, Monterey, California, March, 2009.

[8] S. Golomb and R. Scholtz, “Generalized Barker sequences (transformations with correlation function unaltered, changing generalized Barker sequences),” *IEEE Trans. Inf. Theory*, vol. 11, pp. 533-537, Oct. 1965.

[9] C. Lo and C. Furse, “Modeling and simulation of branched wiring networks,” *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 23, no. 2, pp. 143-146, June 2008.

[10] R. N. Bracewell, *The Fourier Transform and its Applications*, 3rd Edition, McGraw-Hill International Editions, pp. 61, 2000.

[11] Ansoft High Frequency Structure Simulation (HFSS), Ver. 13, Ansoft Corporation, 2010.

[12] T. C. Edwards, *Foundations for Microstrip Circuit Design*, Wiley, Great Britian, 1981.

[13] C. H. Cheng, C. H. Tsai, and T. L. Wu, “A novel time domain method to extract equivalent circuit model of patterned ground structures,” *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 11, Nov. 2010.

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