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TIME REVERSAL FOR SOFT FAULTS DIAGNOSIS IN WIRE NETWORKS

Lola El Sahmarany[1, *], Laure Berry[2, 3], Nicolas Ravot[1], Fabrice Auzanneau[1], and Pierre Bonnet[2, 3]

[1]Embedded Systems Reliability Laboratory, CEA, LIST, Saclay Nano-Innov PC172, 91191 Gif-sur-Yvette Cedex, France

[2]Pascal Institute, University Blaise Pascal, BP 10448, Clermont-Ferrand F-63000, France

[3]CNRS, UMR 6602, IP, Aubiere F-63171, France

Abstract—Time-reversal (TR) invariance of the wave equation in lossless transmission line (TL) is here introduced as an improvement for fault-detection techniques in wire networks. This new approach is applied to reflectometry in wire diagnosis. To test the efficiency of this method, the reverse time algorithm simulated with FDTD (Finite Difference Time Domain) is developed in a one dimension space. It uses a new signal processing and an adapted signal to the wire under test for diagnosing the fault in the wire. In addition, the interest of the convolution product between the incident signal and the output signal from this reverse time method will be also shown and applied in this paper. Through numerical simulations and experimental results measured on coaxial cable, the benefits of this method have been illustrated.

1. INTRODUCTION

Wire networks are present in most modern systems, such as transportation systems, industrial machinery, buildings, nuclear facilities, power distribution systems, etc., where the transmission of information and energy is crucial for their proper functioning. Given that some of these wire networks are responsible for security functions, the necessity of monitoring the wire diagnosis is important to detect and locate electric faults.

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* Corresponding author: Lola El Sahmarany (lola.el-sahmarany@cea.fr).

Generally, two main categories of wire faults are considered: Hard faults (open and short circuits) which produce an important modification in signal propagation along the network and Soft faults (small anomalies, damaged insulation, crushed lines, water infiltration, etc.), which lead to a small modification and are more difficult to detect, especially in complex wire networks. Several testing methods have been developed to detect and locate faults. Reflectometry is one of the most widely applied especially for detecting hard faults. The basic idea of the reflectometry method is to inject a signal in the network under test. As this signal propagates along the transmission line, each discontinuity on the line causes a part of its energy to be reflected. Measuring and analyzing these reflections gives information about the network's status. But in case of soft faults (characterized by weak signatures), it does not provide relevant information. This is because the amplitude ot the reflected wave caused by this type of soft faults can be, in some cases, comparable to the noise level or other residual signals due to impedance discontinuities along the wire network.

Several signal processing methods can be considered to improve fault localization in wire networks [1–6]. This research overcomes the limitations of standard wire diagnosis methods (i.e., time domain reflectometry (TDR)) by proposing a new signal processing method based on time reversal for detecting and locating the soft faults in a wire network. To test how efficient this method is, a Finite-Difference Time-Domain (FDTD) [7] code was used in one dimension space to simulate the propagation of an electrical signal along a line, taking into account its RLGC (per unit length resistance, inductance, conductance, and capacitance) parameters. It is implemented for simulating the effect of the time reversal on the propagation of electrical signals in transmission lines. The feasibility, applicability, and accuracy of the proposed method are investigated by numerical simulation and experimental measurements.

The paper is organized as follows: Section 2 explains how the time reversal is applied to the wire diagnosis. It briefly recalls the tools used in the time reversal procedure:

— the time reversal principle,
— the interest of the convolution product between the reverse signal and the incident signal,
— the propagation on transmission lines.

Section 3 presents different numerical simulations applied to two different network topologies. Section 4 presents two experimental results for the new approach. Finally, a general conclusion recalls the advantages and the limits of this new signal processing method for locating and detecting the faults in networks.

2. TIME REVERSAL METHOD

2.1. Principle

Time reversal method was first introduced in acoustics by M. Fink. It is a method that has proven its efficiency in recent years in different applications like [8–14] acoustics for brain therapy, non destructive testing and under-water telecommunications. In addition, this method is studied and applied to detection and localization of an object or a defect in a complex medium. The principle of the time reversal method is presented in Fig. 1. A transducer captures all the response of a medium from a source, and re-emits the time reversed version of this response into the propagation medium. The signal propagates back and focuses at the initial source taking benefit from the invariance property of the propagation equation with respect to the temporal variable t. We notice that the original transmitted pulse is coherently focused, both temporally and spatially, at the source's position.

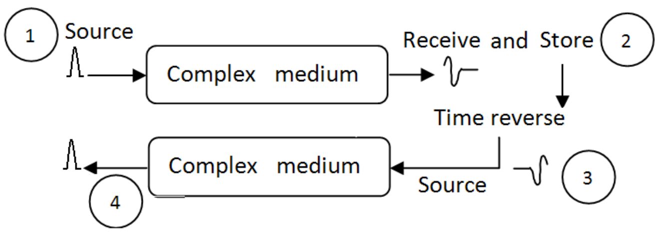

Figure 1. Time reversal process. The schematic explains the principle of time reversal in 4 steps: 1) A source generates a signal which propagates through a complex medium. 2) The received signal is stored. 3) The received signal is reversed and re-radiated into the complex medium. 4) A space time focusing at the original source is observed.

2.2. Convolution Product and Time Reversal

In a recent paper [14], the authors have shown the interest of the convolution product between the reverse signal and the incident signal (that propagates in the medium without any defect) for locating buried objects. The convolution product allows to locate an object, which acts as a secondary source, independently of time. Abstractly, the convolution measures the amount of overlap between two signals. It can be thought of as a mixing operation that integrates the point-wise multiplication of one dataset with another.

2.3. Time Reversal for Fault Diagnosis in Wire Network

Here, a new application of time reversal is presented for fault detection in wire network. The conventional approach to analyze propagation in transmission lines is based on the telegrapher's equations:

$$\frac{\partial v(z,t)}{\partial z} + L\frac{\partial i(z,t)}{\partial t} + Ri(z,t) = 0 \quad (1)$$

$$\frac{\partial i(z,t)}{\partial z} + C\frac{\partial v(z,t)}{\partial t} + Gv(z,t) = 0 \quad (2)$$

where, $v(z,t)$, $i(z,t)$ are the evolution in time (t) and space (z) for voltage and current along the TL.

For lossless transmission lines (i.e., $R = 0 = G$) we notice that the combination of partial differential Equations (1) and (2) leads to time invariant wave equations for both voltage (3) and current (4).

$$\frac{\partial^2 v(z,t)}{\partial^2 t} = \frac{1}{LC}\frac{\partial^2 v(z,t)}{\partial^2 z} \quad (3)$$

$$\frac{\partial^2 i(z,t)}{\partial^2 t} = \frac{1}{LC}\frac{\partial^2 i(z,t)}{\partial^2 z} \quad (4)$$

As the voltage or current and its time-symmetric (i.e., $v(z,t)$ and $v(z,-t)$ or $i(z,t)$ and $i(z,-t)$) are both solutions of the same propagation Equation (3) for voltage and (4) for current, the time-reversed voltage wave allows the reflected signal to return to the original source. Theoretically, the Time Reversal principle is only valid for lossless medium but practically low loss cables can be simulated and provide successful application of the proposed method.

In this application, a probe signal is injected through a cable. The reflected signal is received and saved, and then time reversed and retransmitted through the same cable. A testing port noted $\Im_p$ used for the injected/recorded test signals (Fig. 2) is located at one end of the line. A soft fault, creates a local impedance discontinuity, which behaves like a secondary source generating a transmitted wave and a reflected wave. Then, a TR process can be applied to locate these modifications relative to a healthy reference line.

As illustrated in Fig. 2, the proposed TR signal processing requires three steps applied to two transmission lines (with and without faults):

— In the first and the second steps, a probe signal is injected through $\Im_p$ in the line with and without fault, respectively. The reflected signals $v_{rF}(\Im_p,t)$ and $v_r(\Im_p,t)$ for the line with and without fault, respectively, are recorded at $\Im_p$. The two recorded signals can be obtained experimentally and are used to detect the fault. Additionally, a spatial voltage distribution along the line without fault noted $v_{in}(z,t)$ obtained numerically is saved.

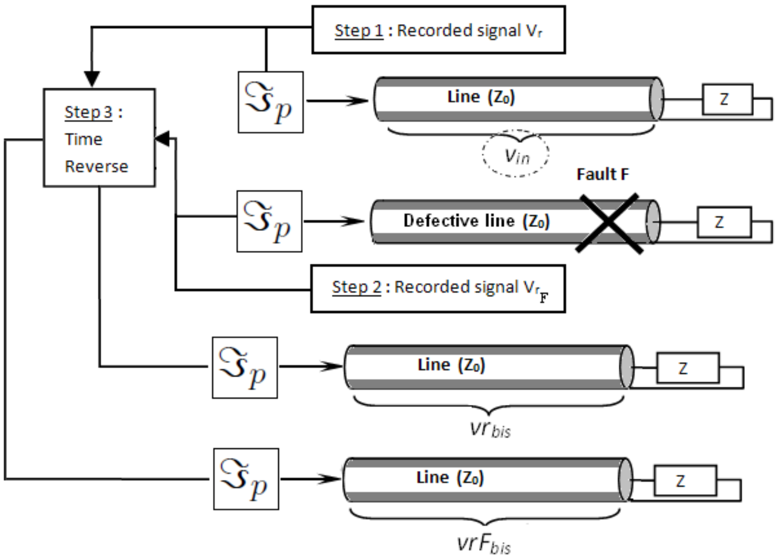

Figure 2. The three steps of the time reversal procedure.

— In a third step, $v_r(\Im_p, t)$ and $v_{rF}(\Im_p, t)$ are time-reversed and re-injected through the testing port $\Im_p$ in a line without fault then consecutive spatial voltage distributions ($v_{r_{bis}}(z, t)$ and $v_{rF_{bis}}(z, t)$) along the line are numerically obtained and saved.

— In a last step, two convolution products are calculated $v_{r_{bis}} * v_{in}$ and $v_{rF_{bis}} * v_{in}$ for correlating the signals which represent the propagation specificities of the line with and without fault, respectively, (5) and (6). Each convolution operation consist in obtaining the area overlap between the two voltages. For example in the Equation (5), the $v_{in}(\tau)$ is time reversed: $v_{in}(-\tau)$ and shifted with a time offset, t, allowing $v_{in}(t - \tau)$ to travel along the τ-axis.

$$v_{r_{bis}} * v_{in} = \sum_{n=0}^{K-1} v_{r_{bis}}(n\Delta\tau) \cdot v_{in}(t - n\Delta\tau)\Delta\tau \quad (5)$$

$$v_{rF_{bis}} * v_{in} = \sum_{n=0}^{K-1} v_{rF_{bis}}(n\Delta\tau) \cdot v_{in}(t - n\Delta\tau)\Delta\tau \quad (6)$$

where, K is the finite number of acquisition.

Then a difference operation between the two convolution products (5) and (6) is calculated. This operation is equivalent to a time filtering process of the voltage variations in the line.

3. SIMULATION RESULTS

3.1. FDTD

The well known, FDTD technique [2] is used to solve the lossless version of telegrapher's Equations (1) and (2). This method provides the time domain response of a transmission line by discretizing in space and time the telegrapher equations. The simulation is done by using a RLCG model of a coaxial cable using MATLAB®. A Gaussian pulse voltage source $v(z = 0, t)$ is assumed. The cable is terminated by a load impedance Z_L. In this method, the position variable z is discretized as Δz and the time variable t is discretized as Δt. The derivatives in TL equations are approximated by finite differences. To ensure stability, we require the length of the spatial cell size Δz to be small compared to the wavelength of the source signal, generally of the order of $\Delta z = \lambda_{\min}/100$.

We implement a TR algorithm with a FDTD code that achieves the reverse time procedure of both current and voltage equations. The FDTD space and time steps used for all simulations in this paper satisfy the CFL (Courant-Friedrichs-Lewy) stability condition. We should note that the accuracy of the solution obtained by the FDTD techniques depends on having sufficiently small temporal and spatial cell sizes.

3.2. Examples

In this paper, two simulations faults are tested. The proposed method shows more accurate results compared to the simulation result of [15, 16]. In addition, it can be applied to different TL configurations (short circuit, open circuit, load impedance).

In [15], the efficiency of the new approach was first evaluated on a point to point matched transmission line and on a wire network made of a simple Y-shaped network (Fig. 3).

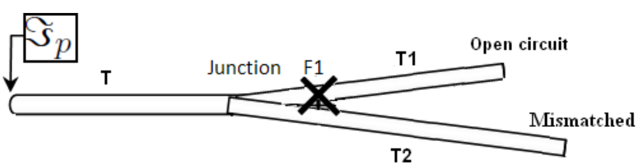

Figure 3. Topology of the wire network.

For the first simulation test, a wire network made of one junction and three transmission lines (RG58 low loss coaxial cable model) T

(2 m), T_1 (2.5 m) and T_2 (4 m) was evaluated. The characteristic impedance is 50 Ω for lines T and T_1 and 100 Ω for T_2. The branch T_1 is left open and T_2 is loaded by an impedance equal to 50 Ω. One single fault is tested. A 28.5% drop of the per-unit-length inductance L leads to an increase of 40% of the per-unit-length capacitance C, which simulates a fault, located at 2.5 m from $\Im_p$ on the line T_1. The voltage pulse is injected in the network at $\Im_p$. The reflected signal v_{rF} and v_r for the line with and without fault, respectively, are recorded (Fig. 4).

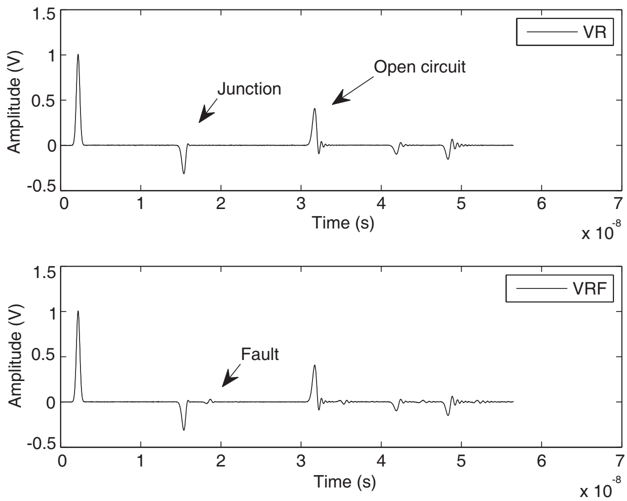

Figure 4. Standard reflectometry (TDR) reflected signals of a TL without fault "VR" and with fault "VRF".

Moreover, to estimate the robustness of the procedure, a random noise with a standard deviation of 1 mV, is added to the recorded signal v_{rF}. In order to reduce noise an autoconvolution step is added after the third step (as we show in (Fig. 5(a))). The TR signal processing result is shown in (Fig. 5(b)). One peak stands out from the noise and matches very well with the position of the simulated fault in the wire network.

The efficiency of the method is also evaluated on a complex wire network made of two junctions and five lossless transmission lines T (4 m), T_1 (3 m), T_2 (6 m) T_3 (3 m) and T_4 (5 m) (Fig. 6(a)). The characteristic impedance Zc is 50 Ω for lines T and T_1, 100 Ω for T_2 and 200 Ω for T_3 and T_4. The branches T_1, T_3 and T_4 are, respectively, terminated by 200 Ω, 300 Ω and 300 Ω loads.

The previous voltage pulse is injected in the network at $\Im_p$. Two

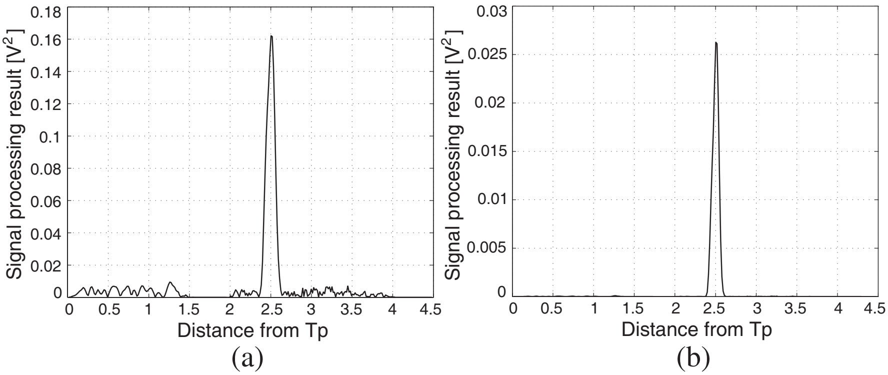

Figure 5. Time reversal reflectometry (TRR) result. Peak detection for one fault localized on the line T_1 (2.5 m from the point $\Im_p$) (Fig. 5(a) after step three and Fig. 5(b) after autoconvolution).

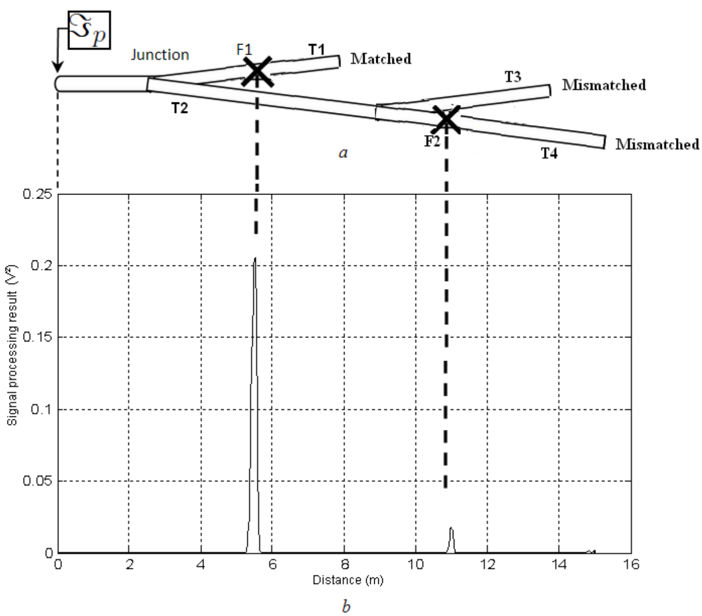

Figure 6. A Time reversal reflectometry (TRR) result. Topology of the wire network (Fig. 5(a)), Peaks detection for two simultaneous faults localized on line T_1 (5.5 m from $\Im_p$) line T_4 (11 m from $\Im_p$).

simultaneous faults are tested. A modification of a per-unit-length parameter, respectively, 71% of L for F_1 and 85% of L for F_2 simulates each fault, located, respectively, at 5.5 m from $\Im_p$ for F_1 on the line T_1 and at 11 m for F_2 on the line T_4. Two peaks stand out clearly and match very well with the positions of the simulated faults in the wire network (Fig. 6(b)).

Table 1 presents an important result: the amplitude of the reflections on the defect (Fig. 6) are much bigger than standard TDR.

In order to test the limit of this new approach, another simulation was done on a complex wire network made of two junctions and five lossless transmission lines T (4 m), T_1 (6 m), T_2 (3 m), T_3 (3 m) and T_4 (4 m). A fault (57% modification of the capacitance) is located at 7 m from $\Im_p$. In this case, the reflected signal of this fault should be masked by the reflected signal of the second junction. Our method enables to cancel the junction peak and to detect more efficiently the defect (Fig. 7).

Table 1. Comparison of the amplitude of the fault peaks obtained with standard TDR and the new approach based on time reversal.

Peak amplitude	TDR	TRapproach	Gain ($10\log_{10}(\lvert \frac{Peak(TR)}{Peak(TDR)} \rvert)$) (dB)
Peak N°1	0.013	0.206	11.999
Peak N°2	0.004	0.018	6.532

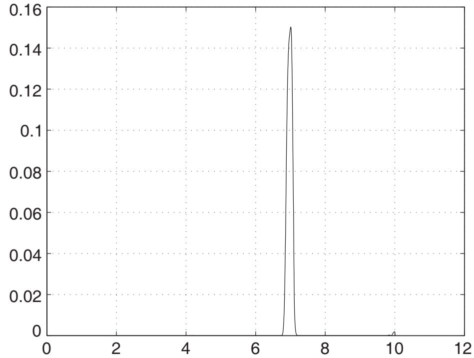

Figure 7. A Time reversal reflectometry (TRR) result. Peak detection for a fault localized on the line T_1 (7 m from the point $\Im_p$).

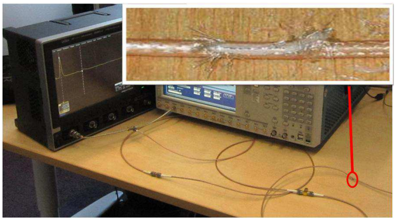

Figure 8. The experimental setup, at the right an arbitrary waveform generator (AWG 7122C 24 GS/s) and an Oscilloscope (Lecroy Waverunner 104Mxi 1 GHz) at the left. We show here the cable with a fault surrounded by a red circle.

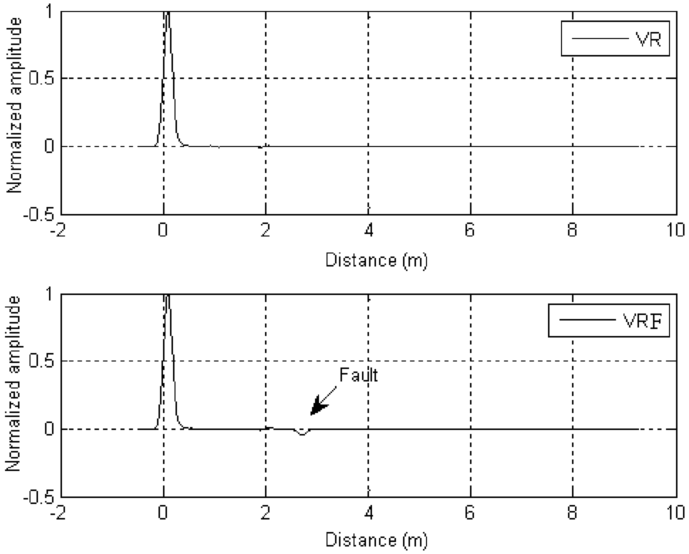

Figure 9. Standard TDR result: It presents the 2 reflected signals of a TL without fault "VR" and with fault "VRF".

4. EXPERIMENTAL RESULTS

The performance of the new approach is now tested on TDR (Time Domain Reflectometry) measurements obtained for a damaged matched SMA coaxial cable of 4 m length [17, 18]. A soft fault, shown in Fig. 8, was made at 2.80 m from the injection point. The outer plastic sheath and the metallic shield have been partially removed on a 1.3 cm long portion of line. An arbitrary waveform generator

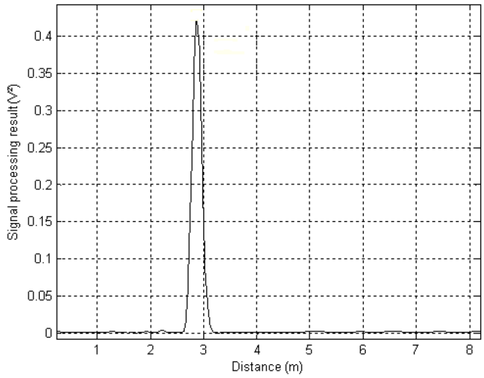

Figure 10. A Time reversal reflectometry (TRR) experimental results. Peak detection for a fault localized on the coaxial cable (2.87 m from the point $\Im_p$).

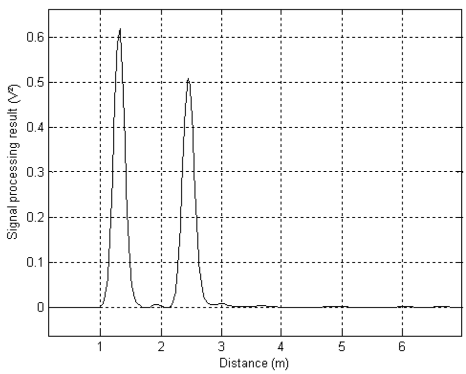

Figure 11. A Time reversal reflectometry (TRR) experimental results. Peaks detection for two fault localized on the coaxial cable (1.32 m and 2.44 m, respectively, from from the point $\Im_p$).

(AWG 7122C 24GS/s) was used to generate and inject the Gaussian pulse (a 1V Gaussian pulse, 2 ns half-height width) into the cable. The reflected signals for a cable with fault and without fault (the two cables should be the same) are measured thanks to an oscilloscope (Lecroy Waverunner 104Mxi 1 GHz) as illustrated in Fig. 9. Using the new approach based on time reversal, we notice that a peak was detected for a fault localized at 2.87 m (as shown in Fig. 10) on the coaxial cable. The amplitude of the reflection on the defect is much bigger than for

Table 2. Amplitudes of the peaks for standard TDR and time reversal reflectometry.

Peak amplitude	TDR	TR approach	Gain $(10\log_{10}(\lvert \frac{Peak(TR)}{Peak(TDR)} \rvert))$ (dB)
Peak N°1	−0.05349	0.6189	10.633
Peak N°2	−0.04758	0.5082	10.286

the TDR results, which means that its detection will be easier using the new approach.

Two other soft faults like above, were made at 1.30 m and 2.45 m from the injection point on a 4 m long SMA coaxial cable. Using the new approach based on time reversal, we notice that two peaks were detected for two faults located at 1.32 m and 2.44 m, respectively, (as shown in Fig. 11) on the SMA coaxial cable. Table 2 shows an important result for the experimental result: the amplitude of the reflections on the defects (Fig. 11) are much bigger than on the standard TDR. This clearly shows clearly the efficiency of the new approach over standard TDR.

5. CONCLUSION

This article has proposed a time reversal procedure to detect and locate "soft faults" in a transmission line or in a wire network. Several simultaneous faults can be accurately located depending on the bandwidth of the test signal and the configuration of the wire networks. Experimental validations were carried out to confirm the interest of this method. So, in order to ensure the safety of an entire electrical system, the new method could be used to continuously monitor the cable and to prevent electrical failures, which could have critical consequences.

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