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WIRE TROUBLESHOOTING AND DIAGNOSIS: REVIEW AND PERSPECTIVES

Fabrice Auzanneau*

CEA, LIST, CEA Saclay Nano-INNOV, PC 172, F-91191 Gif sur Yvette, France

Abstract—Electrical cables of all types are subject to aggressive environments that can create defects or accelerate aging. Many application domains require diagnosis methods and tools. Among many methods, reflectometry has proven to be the best candidate and can be easily applied to the detection and localization of hard defects, while only requiring one access point to the wire. But soft defects are more difficult to track and require new powerful methods. This paper presents a review of the recent state of the art in the field of wired network diagnosis and shows the evolution of future activities in this domain. It provides new perspectives and new research domains are proposed.

1. INTRODUCTION

Electrical cables are everywhere in many fields where the transfer of energy and information is necessary to guarantee the performance of a system. The type and geometry of a cable are different according to the nature of the signal one wishes to transmit, to the voltage level or the environment in which the system evolves. Energy networks use cables whose constitution is different from those used for data because these cables are designed to distribute energy on very long distances throughout a country or a continent. A new 1000 km long High Voltage Direct Current (HVDC) energy cable is soon to be deployed between Iceland and Great Britain to increase green energy supply in the UK [1]. Aeronautics and space are perfect examples of applications where several types of cables are used with cumulated lengths up to 500 km for big aircrafts, in regular increase since the last forty years. The use of cables that are light, flexible, compact, of a great reliability and

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* Corresponding author: Fabrice Auzanneau (fabrice.auzanneau@cea.fr).

resistant to various environments are the main requirements imposed by these industries.

One day or another, a cable network will show signs of weakness or aging involving the appearance of defects. These anomalies can be the origin of dysfunctions and imply serious consequences for the system or the environment. In many sectors, a great number of embedded systems dedicated to safety and comfort communicate with increasingly important data rates in order to fulfill severe real-time constraints. These constraints imply to have at disposal a trustworthy physical support to guarantee both quality of service and reliability. Unfortunately, cable problems start to appear and multiply whereas the request for systems reliability is increasing. New power-line communication (PLC) transmission technologies made it possible to reduce harnesses complexity. But on the other hand, they increased the need to have high quality connections free from defects. It is thus necessary to have diagnosis methods and systems dedicated to wired networks in order to guarantee that the harness ensures faithful information and power transmission.

This paper presents a review of the current and recent state of the art in the field of wired network diagnosis, and is organized as follows: after an overview of different operational contexts in Section 2, Section 3 presents the principles of the main diagnosis methods, Section 4 covers upstream modeling aspects, then sections 5 and 6 will discuss diagnosis strategy problems and future studies.

2. CONTEXT

Wired networks are considered as the backbones of complex systems. The increase of the complexity of modern systems has come with the increase of wire lengths. This is true for embedded systems as well as infrastructures and buildings. The cumulated length of electrical wires in a modern car is more than 4 km, compared to a few hundred meters 30 years ago. Higher than 40 km in modern fighter aircraft, it is close to 200 km in high speed trains and 400 km in recent civil planes [2] and can be estimated around 5000 km in a nuclear power plant. Considering more than 40000 km of railways in a large country, one can see that this kind of infrastructure can use almost 1 million km of electrical wires.

Whatever their application domain, wires can be subject to aggressive environmental conditions which may create defects. These defects can have dramatic consequences if the wires are parts of safety critical systems, i.e., systems whose failure may cause death or injury to people, loss or severe damage to equipment or environmental harm.

Health equipment, transportation systems and nuclear power plants are a few examples of such systems. It is therefore important to quickly detect and precisely locate failures in wired networks as it is usually done for electronic systems.

2.1. Avionics and Space

This was officially recognized in the aeronautics domain at the beginning of this century, after many American studies showed that several hundred wiring faults can be found in wire harnesses of aging aircrafts. The conclusion was that airplanes over 20 years old are virtually guaranteed to have wiring problems [3].

Wire failures can cause deadly accidents such as for TWA flight 800 in 1996 and SwissAir flight 111 in 1998 [4], and were found responsible for the accident of Apollo XIII flight in April 1970 [5]. They can also be the origin of huge costs and aircrafts reduced readiness: in 2004, US Navy has seen as many as 1400 mission aborts caused by wiring problems, and roughly 2 to 3 percent of its fleet grounded for the same reasons. It was recognized that there are an average of 3 fire and smoke events per day in jet transport aircrafts only in the USA and Canada [6].

The overall cost of an "Aircraft On Ground" (AOG) is estimated by several airlines up to USD 150000 per hour. In 2011, a major airline had to cancel around 300 flights after a crack was found in a Boeing 737 fuselage [7]. 79 planes of the same make and model were stuck on ground until necessary repairs were done. It was estimated that the AOG status of these flights cost the airline as much as USD 4 million in lost revenue.

In this context the importance of maintenance is obvious, but it can be a really hard job to locate an insulation breach or even an open circuit in several kilometers of wires running in hard to reach places such as fuel tanks or behind turbines.

2.2. Automotive

Automotive industry is also concerned as it showed in the last ten years a constant evolution of embedded systems which implied the increase in the number of connectors and wired interconnections [8].

Today a great variety of local networks enable the various calculators or Electronic Control Units (ECU) embedded in a car to communicate. The use of these networks increased to a significant degree the weight and complexity of the electrical architecture in cars. In 1950, a Peugeot 203 comprised only 50 wires, while in 1997 the Renault Safrane had from 800 to 1000 wires. The harnesses (Fig. 1)

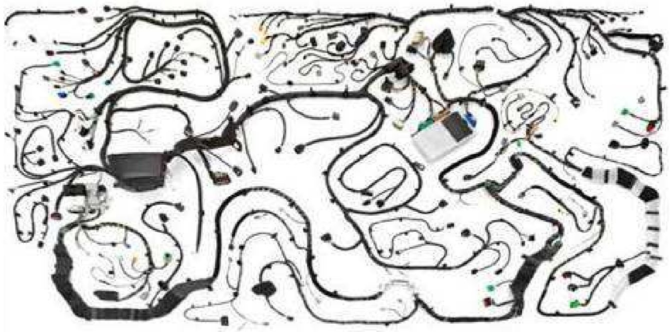

Figure 1. Automotive wire harness.

consist in general of standard low costs, compact cables which have a good temperature behavior. Multiplexing recently appeared in car electrical architecture to reduce the number of wires and connectors, and enabled to add several sensors, actuators or instruments, which contributed to increase the harness complexity, the opposite of its original goal.

Today, the complexity of the electrical network of a modern car is such that the search phase needed to locate and repair a wire defect in the harness can take up to 2 days for a skilled mechanic. This is very expensive, both for the garage and the customer, because the troubleshooting process often implies changing several electronic parts. Furthermore, some automotive Original Equipment Manufacturing (OEM) companies have reported that 70% of returned ECUs were tested free from defects, emphasizing the need for wire diagnosis tools in garages.

Furthermore, security stakes will arise for hybrid and electrical vehicles, in which power cables are considered critical (see Section 5.3).

2.3. Infrastructure and Buildings

Modern buildings are equipped with very long cables both for energy supply and telephone or computer network. The Twin Towers of the World Trade Center in New York housed more than 19000 km of electric cables (more than 85 km per floor), and nuclear power plants contain up to 5000 km of cables, some of them potentially affected by radiations which can cause premature aging and reduce their ability to sustain accidental conditions.

Cumulated lengths of wire are more important for infrastructures such as railways, which imply hard and expensive maintenance needs. Control and repair of signal cables along railways require several thousands working hours per year in large countries, with constraining procedures. Signal must be stopped, which has important consequences on traffic.

3. DIAGNOSIS METHODS AND REFLECTOMETRY

All these application contexts emphasize the need for accurate tools able to detect and locate defects in wired networks. Visual inspection cannot be the only available method anymore, especially when maintenance workers can cause additional defects simply by walking on wires or pulling them to better examine some hidden connectors.

The need for new and practical wire diagnosis methods was understood around the year 2000, and several electric and non-electric diagnosis methods have been studied and developed.

3.1. Wire Diagnosis Methods

In July 1999, a short circuit caused a fault in the two main engine computers five seconds after Columbia STS-93 space shuttle launch, leaving the crew one failure away from an emergency landing attempt [9]. It should be noted that there were more than 100000 cables for a total length of 400 km in the space shuttle, some of them deeply buried and very hard to inspect. This led NASA to release a report [10] examining and classifying many test and diagnosis methods for wiring interconnections.

Various methods were studied, from visual inspection, ultrasonic guided wave, X-ray, infrared and thermal imaging, and many electrical methods such as: continuity, isolation, capacitance and resistance measurement, dielectric withstanding voltage (also known as "High Pot"), impedance spectroscopy, standing wave ratio and reflectometry. Other methods such as Pulse Arrested Spark Discharge [11], Excited Dielectric Test [12] and Line Impedance Resonance Analysis [13] were also proposed later, and can be viewed as reflectometry variations.

Table 1 summarizes the main advantages and disadvantages of these methods. Among all known diagnosis methods, reflectometry is the most promising one.

3.2. Reflectometry

Reflectometry is a high frequency method with the advantage of using only one cable (the cable under test itself) and of obtaining an image of its state while measuring from only one end (Fig. 2). Similarly to Radar, reflectometry injects a probe signal at one end of the cable under test. This signal propagates along the cable and each impedance

Table 1. Comparison of diagnosis methods.

Method	Advantages	Disadvantages
Visual inspection	Provides location information	Strongly depends on the operator, requires full access to the cable
X rays	Can detect any kind of defect, provides location information	Requires heavy systems
Ultrasound guided wave	Can detect insulator defects	Needs complete access to the cable, not suited for branched wires
Infrared thermal imaging	Provides location information	Requires complex imaging system, not suited for every kind of fault (the fault must create a hot spot)
Continuity measurement	Provides quick continuity information	Requires two access points to the cable, does not give location information
High Pot	Can detect insulator defects	May further damage the cable under test, requires heavy systems
Reflectometry	Only needs one access point, provides location information, suited for complex topology networks, can be embedded	See Section 3.3

discontinuity met (junction or defect) returns a part of its energy towards the injection port (Fig. 3). The analysis of the received signal provides information on the presence, the localization and the type of these discontinuities. This information is very rich and valuable for maintenance operators.

Reflectometry includes two main families: Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR). TDR is the easiest to understand: it periodically injects a specific probe signal and the measured signal is basically made of multiple copies of this signal delayed in time. For each copy, the delay is the round trip time necessary to reach the discontinuity from the injection point. This composite signal is called "reflectogram". So, knowing or evaluating the propagation velocity enables to locate the discontinuity or defect

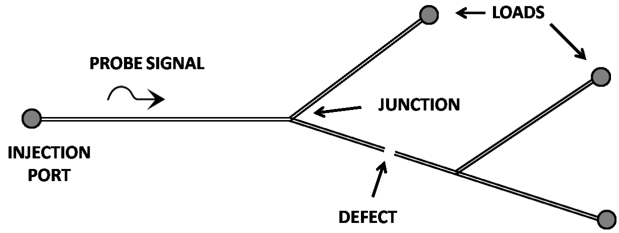

Figure 2. Network under test.

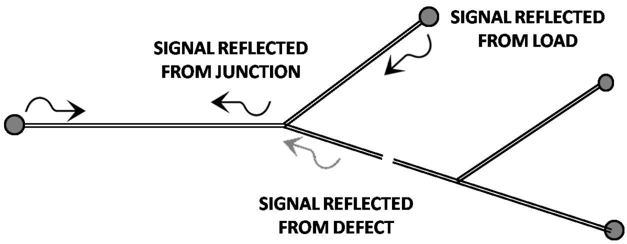

Figure 3. Principles of reectometry.

which created each copied signal, and the shape and amplitude of this signal provide information on the nature of the defect.

FDR is more difficult to understand and to interpret, as it injects a set of sine waves and analyses the standing wave due to the superposition of the injected and reflected signals [14]. This analysis is quite easy for a simple point to point cable but it becomes too complicated for complex networks.

3.2.1. Time Domain Reflectometry

Most basic TDR systems use a Gaussian pulse or voltage step as probe signals, but to fulfill Electromagnetic Compatibility (EMC) or other specific constraints of embedded systems or noise robustness, one requires different signals. Moreover, the energy of the pulse signal of standard TDR is limited: to counter the cable's propagation attenuation one needs to increase the amplitude of the signal. Another way to increase the energy is to use pulse compression [15], this is done by injecting a binary pseudo random signal [16] and calculating the correlation of the measured signal with the injected one to obtain the reflectogram. The idea of linking TDR and spread spectrum techniques led to novel methods using pseudo random binary sequences [17] as test signals, later refined as Sequence Time Domain Reflectometry (STDR [18]) and Spread Spectrum TDR (SSTDR [19, 20]). Maximum

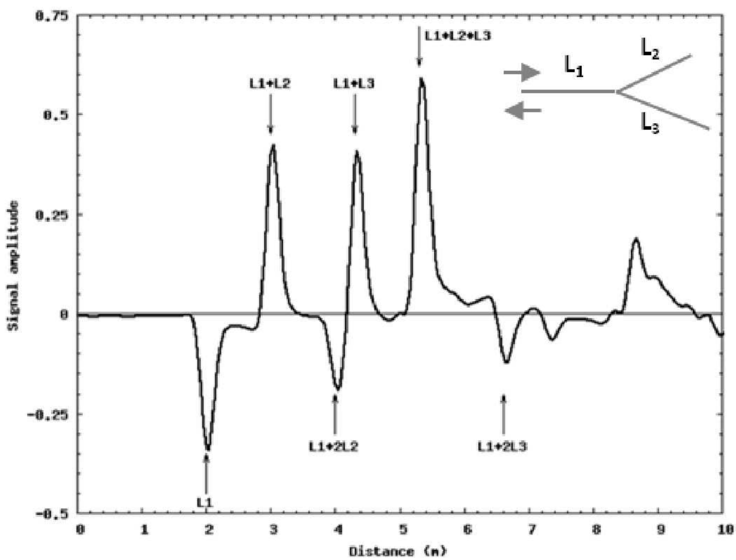

Figure 4. TDR simulation result for a Y shaped network with $L_1 = 2\,\mathrm{m}$, $L_2 = 1\,\mathrm{m}$ and $L_3 = 2.3\,\mathrm{m}$, with open circuits at lines ends (from [22]).

Length Sequences (MLS) have very sharp correlation functions, which make them very interesting for diagnosis [21], but other similar signals may also be used.

TDR methods are well suited for the diagnosis of complex topology networks. They provide a reflectogram (Fig. 4 [22]) where each peak can be associated with one discontinuity along the cable or the network.

But the propagation of a high frequency signal (up to 200 MHz, sometimes higher than 1 GHz) in a cable is subject to two phenomena: attenuation and dispersion [23]. Attenuation decreases the amplitude of the signal during propagation, and dispersion changes its shape along the cable. This is due to the fact that the velocity of propagation depends on the frequency: low frequency components of the signal will propagate differently (slower) from high frequency ones (see Section 4.3). The main consequence is the reduction of location accuracy of the defects for long distances.

3.2.2. Frequency Domain Reflectometry

FDR determines the distance to the defect by the analysis of the standing wave created on the wire by the interference of the injected and reflected signals. The simplest method, called Standing Wave Reflectometry (SWR [24]), measures maxima and nulls in the standing wave to provide location information. Frequency Modulated Carrier Wave (FMCW [25]) and Phase Detection FDR (PDFDR [26]) methods measure frequency shift and phase shift between these waves.

FDR seems unsuited to complex topology networks, as the interactions of a great number of shifted waves is very difficult to analyze. However, when these methods were proposed, FDR was easier and cheaper to implement than TDR. But the huge improvement of electronic components over the last ten years (FPGA and DSP, high bandwidth converters, etc.), mainly due to the rise of wireless communication, made it simpler to implement TDR based methods.

In the rest of this paper, we will focus on TDR based diagnosis methods.

3.3. Performances of Reflectometry

The most interesting performances of reflectometry concern detection and location accuracy. Once a defect is detected, in order to repair it a maintenance operator must get access to the wires by removing panels, which are positioned by several screws. This can be quite a time consuming task if the operator has to remove several panels before finding the one that conceals the defect. Then, an accurate location information is needed to focus directly on the good panel. This emphasizes the fact that the reflectometry based troubleshooting tool must be linked to or used in conjunction with a Computer Aided Design (CAD) model of the harness inside the system (e.g., car or airplane), as the wires may follow a complicated path.

Most TDR methods described above can achieve a location accuracy of only a few percents of the length of the wire under test up to a few hundred meters long. Long cables suffer from attenuation and dispersion which greatly reduce the location accuracy. Indeed, the peaks of the reflectogram (Fig. 4) must be very sharp if one wants to provide a precise estimation of their location. But sharp peaks mean the use of high frequency (if standard TDR is used) or high data rate signals (for STDR-based methods). So, the precise detection of the edge of the peaks requires powerful data processing or very quick sampling, which increases the complexity and the cost of the diagnosis system. Alternative methods have been proposed, such as the use of a Vernier [27] or oversampling [28] techniques.

However, another limitation to accuracy is due to the precision of the knowledge of the propagation speed V_p of the signal. TDR systems only measure a round trip time τ, then the distance to the defect is obtained by (1).

$$d = \frac{V_p \tau}{2}. \tag{1}$$

Any uncertainty on the value of V_p will decrease the accuracy on the value of the distance to the defect. But, we have seen earlier that the propagation speed depends on the frequency. Then, as the probe signal's bandwidth may be quite large, it is not possible to precisely define the propagation speed for the whole signal. This will be explained in more details in Section 4.3.

One last limitation of TDR methods is the so-called "blind zone". If the TDR system is not matched to the intrinsic impedance of the cable, a part of the energy of the injected signal is directly sent back, without even going inside the cable. This creates an additional high amplitude peak at the beginning of the reflectogram which may hide a defect close to the injection point. One way to counter this is to use distributed reflectometry [22] as shown in Section 5.1.

3.4. Types of Wire Defects

Among the most often met defects are short-circuits and open circuits which are the sources of many fires or signal losses [10]. They are called "hard defects", and are characterized by the fact that they prevent any signal from going further away.

Opposite to hard defects are of course "soft defects", which can be of very different kinds [29] and are more difficult to find. A study made by the Aging Transport Systems Rulemaking Advisory Committee (ATSRAC) [30] on 6 different aircrafts has shown that chafing, defined as "*localized damage to the insulation or shielding of a wire*" [31] accounts for 30% to 50% of all detected wiring faults.

Reflectometry methods have different behaviors with hard and soft defects. A hard defect is characterized by a reflection coefficient, defined as the ratio of the amplitude of the reflected wave to that of the incident wave, equal to ± 1. On the reflectogram, the peak associated to a hard defect is always of high amplitude, much higher than noise and easy to detect. On the contrary, a soft defect produces a very low amplitude peak, which can be hidden among various noise sources. This is due to the fact that the probe signal is sensitive to impedance variations along the cable [32], and soft defects only produce very small impedance changes. Their reflection coefficient is very low, as will be shown in Section 4.4.

4. MODELING AND SIMULATION

To better understand how reflectometry works, and to help interpret the reflectogram, the use of a physical model and numerical simulation is very useful.

Usual TDR models calculate the output signal $s_o(t)$ as the convolution of the input signal $s_i(t)$ and the impulse response of the network, often denoted $h(t)$:

$$s_o(t) = s_i(t) * h(t). \tag{2}$$

The simplest model, as said in Section 3.2, states that the cable sends back multiple copies of the input signal with amplitudes α_i delayed by times t_i:

$$h(t) = \sum_i \alpha_i \delta(t - t_i) \tag{3}$$

where δ is the Dirac pulse. In the rest of this paper, uppercase letters will refer to frequency domain functions, and lowercase to time domain ones.

4.1. RLCG Model of a Transmission Line

One well known model for a transmission line is the so-called "*RLCG* model" [33] which divides a wire of length l into several very small portions of length dx, each of them being represented by the equivalent electric model of Fig. 5. The lumped elements R and L account for loss and energy storage in the conductors, C and G for insulation and loss in the insulator. They are often given as per unit length values.

The application of Kirkhoff's laws provides the following equations:

$$\begin{aligned} \frac{\partial v(x,t)}{\partial x} &= -R\imath(x,t) - L\frac{\partial \imath(x,t)}{\partial t} \\ \frac{\partial \imath(x,t)}{\partial x} &= -Gv(x,t) - C\frac{\partial v(x,t)}{\partial t} \end{aligned} \tag{4}$$

which can be studied either in time or frequency domains. The formulas for R, L, C and G depend on the type of wire under study and its geometry [34], but most often L and C can be considered constant

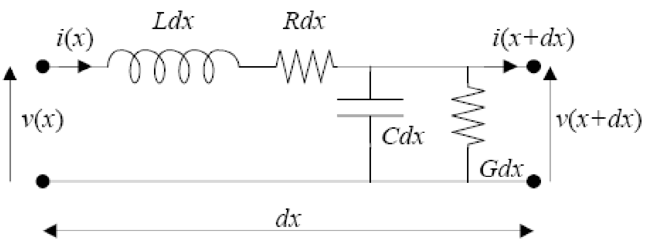

Figure 5. RLCG model of a short cable portion of length dx, $\imath$ is the current, v the voltage.

(independent of the frequency) [22]. This model can be extended to bundles (i.e., Multiconductor Transmission Lines) [35] to account for crosstalk and line interference phenomena [36].

4.2. Time Domain Simulation

Time domain simulation allows to follow the reflectometry signals as they travel along the wires of the network. Apart from commercial full Maxwell solvers, such as CST MWS [37], Finite Difference Time Domain (FDTD) method [38] provides a quick result, as it only requires a 1D mesh of the wire [39]. Voltage and current values are computed at integer and half integer values of the cell size Δx [40] using a standard leapfrof scheme. FDTD simulation can help understand the propagation of signals along the wire [38] or in a bundle [42] but it cannot take into account the variations of R and G with frequency.

4.3. Frequency Domain Simulation

Frequency domain model is capable of taking these drawbacks into account. The simulation model in the frequency domain can be written using the formalisms of the scattering parameters or the $ABCD$ matrix.

The scattering matrix relates outgoing and incoming waves in a quadripole. For the circuit of Fig. 5, the S matrix is given by (5).

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} 0 & e^{-\gamma dx} \\ e^{-\gamma dx} & 0 \end{bmatrix} \tag{5}$$

where γ is the propagation constant, given by:

$$\gamma(\omega) = \sqrt{(R + jL\omega) \cdot (G + jC\omega)} \tag{6}$$

with $j^2 = -1$ and $\omega = 2\pi f$ the pulsation. For an homogeneous line of length l, the S matrix is given by (5) where dx is replaced by l. The characteristic impedance of this line is:

$$Z_c(\omega) = \sqrt{\frac{R + jL\omega}{G + jC\omega}}. \tag{7}$$

An accurate frequency domain model can be derived from these equations because the reflectogram is merely the reflection coefficient of the line at the injection point. For a simple point to point line of length l, it is given by

$$H = e^{-2\gamma l}\rho_L = e^{-2\gamma l}\frac{Z_L - Z_c}{Z_L + Z_c}. \tag{8}$$

where ρ_L is the reflection coefficient at the load [43]. This model can be extended to the case of a complex topology network and provides accurate results [44]. The reflectogram in the time domain is obtained using inverse Fourier transform.

Equation (6) shows that the propagation constant is a complex function: its real part accounts for attenuation and its imaginary part for propagation. If we use the usual definition of the group velocity, i.e., $v_g = \partial\omega/\partial\gamma$, this also leads to a complex function. We then propose to define the propagation speed as

$$\frac{1}{V_p} = \frac{\partial \Im(\gamma)}{\partial\omega} = \frac{\partial\left(\gamma(\omega) - \overline{\gamma(\omega)}\right)}{2j\,\partial\omega} \tag{9}$$

where we note $\Im(z)$ the imaginary part of a complex number z, $\Re(z)$ its real part, $\|z\|$ its modulus and $\bar{z}$ its conjugate. Then, seeing that $\overline{\gamma(\omega)} = \gamma(-\omega)$, we calculate the partial derivatives using (6).

$$\begin{aligned} \frac{\partial\gamma(\omega)}{\partial\omega} &= \frac{jL}{2Z_c} + j\frac{CZ_c}{2} \\ \frac{\partial\gamma(-\omega)}{\partial\omega} &= \frac{-jL}{2\overline{Z_c}} - j\frac{C\overline{Z_c}}{2}. \end{aligned} \tag{10}$$

The velocity of propagation is then given by:

$$V_p = \frac{2}{\Re(Z_c)}\left(\frac{\|Z_c\|^2}{C\|Z_c\|^2 + L}\right). \tag{11}$$

Note that, for the lossless case, the characteristic impedance reduces to $Z_c = \sqrt{L/C}$ and (11) becomes:

$$V_p = \frac{1}{\sqrt{LC}} \tag{12}$$

which is the usual formula. Fig. 6 shows the variations with frequency of the reduced propagation speed V_p/c where c is the speed of light in vacuum, for a standard twisted pair used in railway infrastructures. We can see that, even if R is constant, the velocity of propagation is not constant with frequency (although it tends towards (12) for high frequencies), which gives rise to the dispersion phenomenon seen in Section 3.2. One easy way to reduce dispersion is to select a probe signal whose spectrum is in the frequency band where the propagation velocity is constant.

4.4. The Problem of Soft Defect Detection

We have seen in Section 3.4 that soft defects are difficult to detect because they produce very small local impedance variations. Using the $ABCD$ matrix formalism in the frequency domain, we can derive

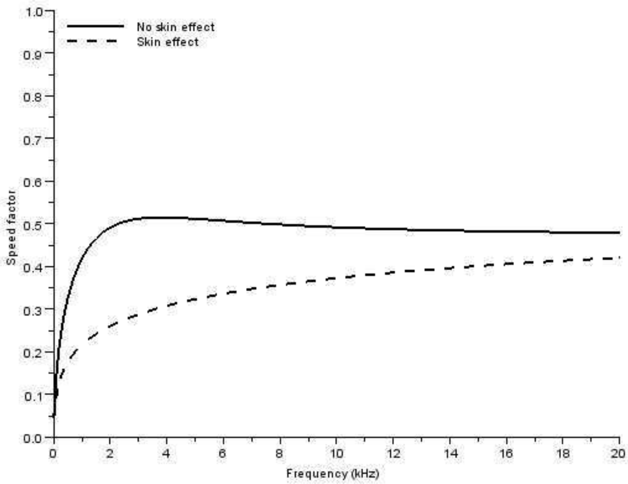

Figure 6. Reduced propagation speed V_p/c for a constant lumped resistance R (plain curve) and with skin effect (dash curve).

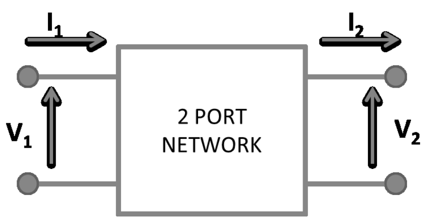

Figure 7. Notations for the $ABCD$ matrix formalism.

a simple model for a soft defect. Fig. 7 and Equation (13) define the notations.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}. \tag{13}$$

We suppose that a soft defect, defined as a small variation of one or more of the R, L, C and G parameters, appeared at the distance l_1 and over the length d of a point to point line of length $l \gg d$.

The $ABCD$ matrix of a line of length l is given by (14):

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_l = \begin{bmatrix} \cosh\gamma l & Z_c \sinh\gamma l \\ \frac{\sinh\gamma l}{Z_c} & \cosh\gamma l \end{bmatrix}. \tag{14}$$

This can be simplified for the defective portion because of the assumption $|\gamma_d\, d| \ll 1$:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_d = \begin{bmatrix} 1 & Z_d\gamma_d d \\ \frac{\gamma_d d}{Z_d} & 1 \end{bmatrix}. \tag{15}$$

We now cascade the $ABCD$ matrices of the 3 portions of the cable

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{l_1} \cdot \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{d} \cdot \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{l_2} \tag{16}$$

where $l_2 = l - l_1 - d$ is the length of the portion after the defect. We call $\epsilon = Z_d/Z_c - 1$. In the case of a short circuit at the end of the line, we can derive using the formulas in Appendix A the reflection coefficient of the line with the defect (similar formulas can be obtained for any load at the end):

$$H_{sc} = \frac{-e^{-2\gamma l}(1 - \gamma_d d) + \gamma_d d\epsilon e^{-2\gamma l_1}}{1 + \gamma_d d + \gamma_d d\epsilon e^{-2\gamma l_2}}. \tag{17}$$

The fraction can be developed as a power series:

$$H_{sc} \simeq \gamma_d d\epsilon e^{-2\gamma l_1} - e^{-2\gamma l}(1 - 2\gamma_d d) + \gamma_d d\epsilon e^{-2\gamma(l+l_2)} \tag{18}$$

which shows 3 distinct signals:

(i) Round trip to the defect : $\gamma_d d\epsilon e^{-2\gamma l_1}$,

(ii) Round trip to the end of the line: $-e^{-2\gamma l}(1 - 2\gamma_d d)$,

(iii) Multiple bounce between the defect and the end of the line: $\gamma_d d\epsilon e^{-2\gamma(l+l_2)}$.

This shows that the amplitude of the soft defect signature $\gamma_d\ d\epsilon$ is very small and explains why such a defect is difficult to detect using reflectometry, as verified experimentally in [45]. Similar models have been presented and extended in [46, 47] for a multiconductor transmission line.

One solution to this problem is to use very high frequency sharp edge signals [48] or multiple high frequency signals [49], but the higher propagation attenuation strongly limits the distance of detection.

Recent works [50] have proposed a new time-frequency domain method called Joint Time-Frequency Domain Reflectometry (JTFDR), based on the use of a chirp signal with a Gaussian envelope and a time-frequency cross-correlation function [51] which amplifies small signals, such as soft defects contributions, up to a level comparable to hard defects. This very efficient diagnosis method has been improved in [52] and applied to the detection of soft defects as well as connectors in transmission lines [53]. This is very helpful for maintenance operators, as the relative position of connectors and defects helps locating them.

Other methods rely on advanced data processing tools, one of the most efficient being the Hilbert Huang Transform (HHT) [54], an empirical modal decomposition method fitted to the study of non-linear non-stationary signals. The HHT is a time-frequency analysis which does not require any prior decomposition basis, the signal is decomposed into a finite and small number of intrinsic mode functions (IMFs) that reflect its local properties. This makes it very useful for soft defects detection using PDFDR [55] or Time-Frequency Domain Reflectometry (TFDR) [56].

Many promising studies have shown that soft defect detection and localization is achievable in laboratory conditions, but there remains some work before an industrial tool can be applied to operational cables.

5. DIAGNOSIS STRATEGY

As the maturity of diagnosis methods is increasing, it is important to know how to use them: the Diagnosis Strategy studies the optimal number and location of diagnosis systems, their interaction with the network, the monitoring period, etc. It can be derived differently, depending on the objectives and constraints of the application, as explained in the following sections.

5.1. Embedded Distributed Diagnosis

Confronted to a wire dysfunction, a maintenance operator can plug a troubleshooting system to the cable network to locate the defect: this is external diagnosis. But, more critical applications may require embedded diagnosis [57] for real time monitoring and decision. This implies complying to additional constraints, such as size and cost, and provides new interesting properties:

- Location ambiguity: if the topology of the network is branched, using a single diagnosis system suffers from an ambiguity problem. A defect on the lower branch of the network in Fig. 8 cannot be distinguished from the same defect on the upper branch. To solve this problem, one can use several reflectometry systems, placed at several ends of the network, which have a different perspective

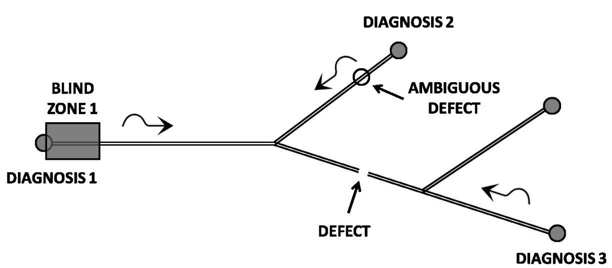

Figure 8. Distributed diagnosis in a complex branched network.

of its topology [58, 59]. The aggregation of all this information provides unambiguous location of the defect. This requires that the signal from one diagnosis system does not interfere with the others thus preventing from creating false alarms: an innovative averaging method based on the use of Walsh Hadamard sequences was proposed in [60].

- Blind zone removal: the blind zone of one diagnosis system (explained in Section 3.3) is automatically canceled as the other systems can remotely access it.

5.2. On Line Diagnosis

Online diagnosis offers the possibility of performing the diagnosis concurrently to the normal operation of the network, i.e., when voltage is on for supply wires and while communication is running for signal cables. This last condition requires harmlessness: diagnosis must not interfere with communication signals, and useful signals must not trigger any false alarm. Recently, a new method called Multi Carrier TDR (MCTDR [61]) was introduced, which injects weighted sums of sinusoids. Based on an original method from [62] it applies the principles of Multi-Carrier Modulation (MCM) to wire diagnosis. One advantage is that it enables to separate the spectra of the native network signals and the probe signal, thus canceling any interference and controlling the wire's radiated fields for Electromagnetic Compatibility (EMC) purpose. This requires more complex post-processing, such as the CLEAN algorithm [63] due to information loss at the zero amplitude frequencies. A new method called "Orthogonal Multi-Tone Time Domain Reflectometry" (OMTDR), based on Orthogonal Frequency Division Multiplexing (OFDM [64]), adds interference robustness, bandwidth efficiency and complete spectrum control. Moreover, it allows communication between the distributed diagnosis sensors to accurately locate faults in branched networks.

5.3. Intermittent Defects Detection

Recent years have seen a great increase in electrical power in aircrafts (1000 kW in an Airbus A350 and 1400 kW in a Boeing 787 [65]) and this tendency may continue in the future with new electrical functions such as brakes, green taxiing, more In-Flight Entertainment (IFE), towards the "more electrical aircraft". Future aircraft electrical network will use high voltage power (230 V AC, 270 V DC) thus increasing the probability of initiating series or parallel arc faults [66]. Similar problems are expected in future hybrid or electrical vehicles, as fuel cells provide up to 300 V DC voltage.

An arc fault creates an intermittent plasma through air between two conductors, which can be seen as a short-circuit during a very short instant. It is not easy to estimate the arc fault duration but it is typically less than 1 ms. Online diagnosis systems can be used in this case, provided they can do the measurement process in a shorter time. Modern microelectronic systems, using FPGA or DSP and high speed converters, can achieve a reflectogram acquisition in 1 µs or less, making it possible to catch such intermittent defects.

5.4. Cable and Connectors Aging Monitoring

As defined by IEEE 1064 standard, aging is the occurrence of irreversible deterioration that critically affects performance and shortens useful life of a system [67]. Submitted to aggressive environmental conditions (thermal stress, nuclear irradiation, etc.), a cable can age quicker and become unable to fulfill its function. In Nuclear Power Plants, the integrity of power and Instrumentation and Control (I&C) cables is essential to prove they can sustain accidental conditions and remain operational as long as possible. In this context, cable aging monitoring and estimation provide valuable information to operators.

Cable aging can be seen as slow variations of electrical parameters, very similar to soft defects but all along the wire. Therefore, standard reflectometry methods cannot be applied. A new method, called Time Reversal Reflectometry (TRR [68]), based on Time Reversal theory [69], improves aging detection and provides an accurate tool for aging estimation.

In [70], broadband FDR is used to track the degradation in a vibrating Cu-Sn automotive connector. The aging of the contact, due to the progressive removal of the tin plating, changes its local impedance which can be measured using FDR. Thus, reflectometry based methods can be used to monitor and estimate the aging of electrical cables and connectors.

6. PERSPECTIVES

Several cable diagnosis methods have been studied and developed in the last decades, showing great performances but also limitations. One specific problem is the diagnosis of very long cables, as those which can be found in infrastructures (Section 2.3): signal attenuation and dispersion prevent from accurately locating defects.

A second problem is the handling of propagation homogeneity. A real cable is never 100% homogeneous: the curl of a twisted pair is not exactly the same along the wire, and even a high quality coaxial cable is not really homogeneous [53]. Such inhomogeneity can be mistaken by a reflectometer as soft defects. Time Reversal principles can be used to improve soft defects detection [71, 72], but a new method called Matched Pulse Approach [73] provides new perspectives for this problem. It uses a self-adaptive signal which is adjusted to the network under test [74], thus propagating information about the inhomogeneity. This matched signal helps to cancel the effects of the cable itself and focus on the defects [75].

Another interesting application of reflectometry is topology reconstruction: if the branched network's shape is unknown, how to find the exact defective branch and characterize the defect? The use of optimization methods [76], neural networks [77], information inference [78] or Bayesian models [79] complements TDR's performances and provides a much more complete tool. It seems possible to give the exact location of a hard defect inside an unknown complex branched network with a single measurement and the adequate post-processing tool.

This raises the more complex problem of the model inversion: how to reconstruct the impedance or $RLCG$ profiles along the cable using reflectometry data [80]? Inverse scattering transform applied to Zakharov-Shabat equations enable to compute the values of the lumped electrical parameters of a lossy transmission line [81]. Experimental results reported in [82] show the possibility of reconstructing a changing impedance profile along a twisted pair, which enables to precisely locate a connector half way of the line.

We have exposed in this paper the need for cable diagnosis in various application domains, and presented the theoretical bases of reflectometry based methods. The important problem of soft defect detection has been emphasized and explained, and several new solutions have been presented. The stakes and constraints of embedded and on-line diagnosis have been shown, together with the best suited TDR based methods, and the bases of Diagnosis Strategy have been settled.

Wire prognosis would be the ultimate step in the series of work described in this paper. Being able to predict the time of occurrence of a wire defect would save a great deal of efforts and money. Soft defects can be seen as the premises of future hard defects which have irreversible consequences and require repair to restore the quality of service: soft defect diagnosis is then the first step. JTFDR was used in [83], together with a modified Arrhenius model, to estimate the Remaining Useful Lifetime (RUL) of a coaxial cable. However, there remains a lot of theoretical and experimental work to do before predictive maintenance tools can accurately calculate the remaining lifetime of a cable or harness.

APPENDIX A. REFLECTION COEFFICIENT OF A DEFECTIVE LINE TERMINATED BY SHORT AND OPEN CIRCUITS

Details of the formulas in Section 4.4.

Starting from (16) and setting:

$$\begin{aligned} C_{1,2} &= \cosh \gamma l_{1,2} \\ S_{1,2} &= \sinh \gamma l_{1,2} \end{aligned} \tag{A1}$$

we obtain, using (15):

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} C_1 & Z_c S_1 \\ \frac{S_1}{Z_c} & C_1 \end{bmatrix} \begin{bmatrix} 1 & Z_d \gamma_d d \\ \frac{\gamma_d d}{Z_d} & 1 \end{bmatrix} \begin{bmatrix} C_2 & Z_c S_2 \\ \frac{S_2}{Z_c} & C_2 \end{bmatrix} \tag{A2}$$

Developing this equation provides:

$$\begin{aligned} A &= \cosh \gamma l + \left(S_1 C_2 \frac{Z_c}{Z_d} + C_1 S_2 \frac{Z_d}{Z_c} \right) \gamma_d d \\ B &= Z_c \sinh \gamma l + \left(C_1 C_2 Z_d^2 + S_1 S_2 Z_c^2 \right) \frac{\gamma_d d}{Z_d} \\ C &= \frac{\sinh \gamma l}{Z_c} + \left(\frac{C_1 C_2}{Z_d^2} + \frac{S_1 S_2}{Z_c^2} \right) \gamma_d d Z_d \\ D &= \cosh \gamma l + \left(S_1 C_2 \frac{Z_d}{Z_c} + C_1 S_2 \frac{Z_c}{Z_d} \right) \gamma_d d. \end{aligned} \tag{A3}$$

The short circuit at end of line is characterized by $v_2 = 0$ and the equivalent impedance of the defective line is:

$$Z_{sc} = \frac{B}{D} = \frac{Z_c(S_1 C_2 + C_1 S_2) + \left(C_1 C_2 Z_d^2 + S_1 S_2 Z_c^2 \right) \frac{\gamma_d d}{Z_d}}{C_1 C_2 + S_1 S_2 + \left(S_1 C_2 \frac{Z_d}{Z_c} + C_1 S_2 \frac{Z_c}{Z_d} \right) \gamma_d d}. \tag{A4}$$

The reflection coefficient is given by:

$$H_{sc} = \frac{Z_{sc} - Z_c}{Z_{sc} + Z_c} \tag{A5}$$

which, after simplification, leads to (17).

In the open circuit case, $\imath_2 = 0$ leads to:

$$Z_{oc} = \frac{A}{C} = \frac{Z_c(S_1 C_2 + C_1 S_2) + \left(C_1 C_2 Z_d^2 + S_1 S_2 Z_c^2 \right) \frac{\gamma_d d}{Z_d}}{C_1 C_2 + S_1 S_2 + \left(S_1 C_2 \frac{Z_d}{Z_c} + C_1 S_2 \frac{Z_c}{Z_d} \right) \gamma_d d} \tag{A6}$$

which can be simplified, using (A5) as:

$$H_{oc} \simeq \gamma_d d\epsilon e^{-2\gamma l_1} + e^{-2\gamma l}(1 - 2\gamma_d d) + \gamma_d d\epsilon e^{-2\gamma(l+l_2)} \quad \text{(A7)}$$

showing similar signals.

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