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OMTDR using BER Estimation for Ambiguities Cancellation in Ramified Networks Diagnosis

Wafa Ben Hassen #1, Fabrice Auzanneau #2, Luca Incarbone #3, François Pérès *4 and Ayeley P. Tchangani *5,

CEA, LIST, Laboratoire de Fiabilisation des Systèmes Embarqués,
F-91191 Gif-sur-Yvette, France
1 wafa.benhassen@cea.fr
2 fabrice.auzanneau@cea.fr
3 luca.incarbone@cea.fr

* *LGP, ENIT, INPT, Université de Toulouse,*
F-65016 Tarbes, France.
4 francois.peres@enit.fr
5 ayeley.tchangani@enit.fr

***Abstract*—Nowadays, increasing demands for on-line wire diagnosis using reflectometry have imposed serious challenges on signals processing, bandwidth control and interference mitigation. On-line diagnosis aims at detecting and locating faults accurately while the target system is running. In this work, a new reflectometry method, named "Orthogonal Multi-Tone Time Domain Reflectometry" (OMTDR), is proposed. OMTDR, based on Orthogonal Frequency Division Multiplexing (OFDM), is a suitable candidate for on-line diagnosis as it permits interference avoidance, bandwidth control and data rate increase thanks to the use of orthogonal tones and guard intervals. Over the diagnosis function, OMTDR adds communication between sensors to more accurately determine faults position in a multi-branch network using a distributed strategy. OMTDR was tested on a branched network consisting of three cables with different lengths, with sensors at each cable end. Here, the sensors signals are carefully constructed using a resource allocation scheme to use frequencies below and above the prohibited bandwidth, used by the target system, for communication and diagnosis. Simulation results show that the proposed method performs well in a branched wiring network as it permits to detect and locate faults accurately even when the target system is operating.**

I. Introduction

In aging aircraft, increasing demands for regular and thorough wire inspection have imposed serious challenges nowadays. A broken, chafing and corroded wire may lead to an in-flight fire or other disastrous accidents such as the crashes of TWA Flight 800 in July 1996 and Swissair Flight 111 in September 1998 [1]. Several techniques have been proposed in order to detect and locate faults before problem appearance. Reflectometry is considered as the best method for wire diagnosis [2]. The sensor injects a test signal down the wire and then analyses the reflected one due to impedance discontinuities caused by likely existing faults [3], [4].

Nowadays, on-line diagnosis, aiming at detecting and locating faults continuously while wires in use are in-flight, is increasingly attractive. As the native signals presence on live wires may interfere with diagnosis, on-line diagnosis has imposed serious challenges on signal processing, bandwidth control and interference reduction. Recently, different reflectometry methods have been proposed to overcome these challenges. Among them let us mention: Spread Spectrum Time Domain Reflectometry (SSTDR) [5], Multi-Carrier Reflectometry (MCR) [6] and Multi-Carrier Time Domain Reflectometry (MCTDR) [7]. In SSTDR method, the sensor injects a sine wave modulated Pseudo Noise code as a test signal, permitting to diagnose live wires. Although SSTDR has been shown to be feasible for on-line diagnosis, it is still limited in terms of interference avoidance. This problem is partly solved by MCR and MCTDR methods. Both of them, based on multi-carrier principle, employ a summation of harmonically related sine waves using Inverse Digital Fourier Transform. Here, each component magnitude in the frequency domain can be reduced or cancelled leading to bandwidth control. Although MCR and MCTDR are interesting methods for on-line diagnosis, they require a huge post-processing phase to reduce interference.

In a complex wiring network, a distributed diagnosis strategy is crucial to locate faults accurately [8], [9]. The idea is to implement several sensors at different points of the network in order to maximise diagnosis coverage. However, as multiple sensors are making measurements simultaneously, specific signal processing methods are required to avoid interferences among concurrent modules. In [8], authors propose to use a modified SSTDR method where some constraints are imposed on the codes properties (primitive polynomial characteristics, code length and bit rates). Instead of working on the test signal, the proposed method in [9] uses well-chosen weighted average to remove location ambiguities and interference noise thanks to multiple measurements. However, it is important to know that the averaging process is based on the hypothesis that the network impulse responses do not change while the measurements are performed, otherwise, false alarms may be triggered. In practice, this hypothesis may not always be held when the target system is operating. Moreover, the efficiency of this method depends on several parameters such as measurements number, measurement time, noise, interference, etc.

In this paper, a new reflectometry method, named Orthogonal Multi-Tone Time Domain Reflectometry (OMTDR) is proposed. OMTDR, based on Orthogonal Frequency Division Multiplexing (OFDM) [10], is a suitable candidate for on-line diagnosis as it permits interference avoidance and bandwidth control thanks to the use of orthogonal tones and guard intervals [11]. Over the diagnosis function, OMTDR adds communication between sensors to more accurately discriminate ambiguous faults position in a multi-branch network using a distributed strategy. Sensors signals are carefully constructed using a resource allocation scheme to use frequencies below and above the prohibited bandwidth, used by the target network, for communication and diagnosis. Simulation results show that the proposed method performs well in a branched wiring network as it permits to detect and locate faults accurately even when the target system is operating.

This paper is organized as follows. Section II derives a wave propagation model using ABCD matrix. Section III discusses the OMTDR methodology. Section IV proposes a resource allocation algorithm for the existing sensors. Simulation results of OMTDR are described in Section V. Section VI summarizes the paper and draws important conclusions.

II. ABCD Model for Complex Wiring Network

The wave propagation in a transmission line can be modelled by a RLCG circuit model [12]. It is represented by Telegrapher's equations at time t as:

$$\frac{\partial v(x,t)}{\partial x} = -Ri(x,t) - L\frac{\partial i(x,t)}{\partial t}. \quad (1)$$

$$\frac{\partial i(x,t)}{\partial x} = -Gv(x,t) - C\frac{\partial v(x,t)}{\partial t}. \quad (2)$$

where the quantities R (resistance), L (inductance), C (capacitance) and G (conductance) are the electrical per-unit-length parameters. In a lossless transmission line, the quantities R and G are equal to zero. Let $v(x,t)$ and $i(x,t)$ represent, respectively, voltage and current at time t and position $x(0 \leq x \leq l)$ where l is the transmission line length.

Considering a lossless transmission line, the propagation constant γ $(radians/m)$, in the frequency domain, can be expressed by:

$$\gamma = -\omega\sqrt{LC}. \quad (3)$$

where ω is the angular frequency, $\omega = 2\pi f$.

Then, the characteristic impedance of the transmission line is obtained as follows [13]:

$$Z_c = \sqrt{\frac{L}{C}}. \quad (4)$$

Here, the ABCD matrix of wire W_i is used to derive reflection and transmission coefficient formulas in a transmission line where:

$$\begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = \begin{bmatrix} \cosh\gamma_i l_i & Z_c \sinh\gamma_i l_i \\ \frac{\sinh\gamma_i l_i}{Z_c} & \cosh\gamma_i l_i \end{bmatrix} \quad (5)$$

Let's now consider a simple example: Y shaped network consisting of three transmission lines W_1, W_2 and W_3 with the same characteristic impedance Z_c and lengths l_1, l_2 and l_3 respectively, as shown by Fig.1. We assume that sensor

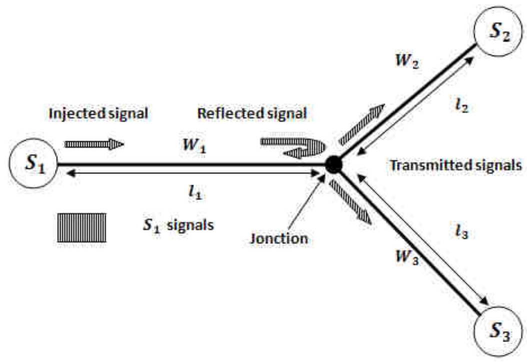

Fig. 1. Y Shaped Wiring Network

S_1 injects at port 1 (line W_1) and the other lines W_2 and W_3 are loaded at their extremities by impedance Z_2 and Z_3 respectively. Y_2 and Y_3, the admittance of lines W_2 and W_3, respectively, are obtained as follows:

$$Y_2 = \frac{C_2 Z_2 + D_2}{A_2 Z_2 + B_2}. \quad (6)$$

$$Y_3 = \frac{C_3 Z_3 + D_3}{A_3 Z_3 + B_3}. \quad (7)$$

In order to compute the equivalent reflection coefficient Γ_1, ABCD matrix (5) of wires W_1,W_2 and W_3 are cascaded. Then, the equivalent impedance at the injection port is given as follows:

$$Z_1 = \frac{A_1 Z_1' + B_1}{C_1 Z_1' + D_1}. \quad (8)$$

where the impedance of W_1 at the junction is expressed as $Z_1' = 1/(Y_2 + Y_3)$. The equivalent reflection coefficient Γ_1 is given as:

$$\Gamma_1 = \frac{Z_1 - Z_c}{Z_1 - Z_c}. \quad (9)$$

The reflection coefficient enables to sensor S_1 to detect and locate faults in terms of distance relative to the sensor on the wiring network. However, as it is sometimes difficult to accurately locate faults in the case of symmetric network where transmission lines lengths l_2 and l_3 are almost the same, a communication between sensors is added to determine faulty wires. This function aims at solving diagnosis ambiguities in the case of complex symmetric wiring networks. Therefore, transmission coefficient needs to be computed in the studied network based on the S-parameters. Here, T_{21} and T_{31} denote the transmission coefficient from S_1 to S_2 and from S_1 to S_3 respectively and are obtained as:

$$T_{21} = \frac{2}{(A_1 + Z_c C_1)\left(A_2 + \frac{B_2}{Z_c}\right) + \left(\frac{B_1}{Z_c} + D_1\right)\zeta_{21}}. \quad (10)$$

$$T_{31} = \frac{2}{(A_1 + Z_c C_1)\left(A_3 + \frac{B_3}{Z_c}\right) + \left(\frac{B_1}{Z_c} + D_1\right)\zeta_{31}}. \quad (11)$$

where ζ_{21} and ζ_{31} are respectively expressed by:

$$\zeta_{21} = (C_2 Z_c + D_2) + (C_3 Z_c + D_3) \cdot \left(\frac{A_2 + B_2/Z_c}{A_3 + B_3/Z_c} \right). \quad (12)$$

$$\zeta_{31} = (C_3 Z_c + D_3) + (C_2 Z_c + D_2) \cdot \left(\frac{A_3 + B_3/Z_c}{A_2 + B_2/Z_c} \right). \quad (13)$$

Using diagnosis and communication functions, the sensor S_1 is now able to locate faults in a branched wiring network. However, this is not possible with the interference due to live signals in the network. Then, OMTDR method is a suitable candidate for on-line diagnosis to avoid interference, bandwidth control and data rate increase as it is explained in the following sections.

III. OMTDR Methodology: Diagnosis and Communication

In OMTDR reflectometry, the test signal injected down the wiring network by sensor S_1 is defined as:

$$x_m(t) = \sum_{n=0}^{N-1} X_{m,n} g_n (t - mT). \quad (14)$$

where m and n refer to the OFDM symbol number and the tone number in the considered OFDM symbol m. Each tone signal $g_n(t)$ is modulated independently by the complex valued modulation symbol $X_{m,n}$ and is expressed as:

$$g_n(t) = \begin{cases} e^{j2\pi n \Delta f t} & \text{if } t \in [-T_G, T_s]. \\ 0 & \text{if not.} \end{cases} \quad (15)$$

where $T_s = \frac{1}{\Delta f}$ and T_G represent respectively useful OFDM symbol duration and guard interval duration. Δf is the frequency distance among two consecutive tones.
As a numerical system is used, the test signal is sampled with the sample interval $\Delta t = 1/B = 1/N\Delta f$. Here, the samples of the transmit signal are denoted by $x_{m,i}$ where $i \in \{0, 1, \cdots, N\}$ and are expressed as follows:

$$x_{m,i} = \sum_{n=0}^{N-1} X_{m,n} e^{j2\pi i \frac{n}{N}}. \quad (16)$$

A. Sensor Diagnosis Function using OMTDR

Respecting the reflectometry principle, the sensor S_1 injects the test signal $x_{m,i}$ down the wiring network. During its propagation, a part of its energy reflects back to the sensor S_1 when it crosses impedance discontinuities such as a fault. Then, the received signal is expressed as:

$$y_{m,i} = hr_{m,i} * x_{m,i} + n_{m,i}. \quad (17)$$

where $*$ is the convolution product and $n_{m,i}$ is the Additive White Gaussian Noise (AWGN) term. The channel impulse response $hr_{m,i}$ is expressed as:

$$hr_{m,i} = \frac{1}{2\pi} \sum_{i=0}^{N-1} \Gamma_1 e^{j\omega i \frac{n}{N}}. \quad (18)$$

where Γ_1 is the equivalent reflection coefficient given by (9). The block diagram of the diagnosis function is shown by

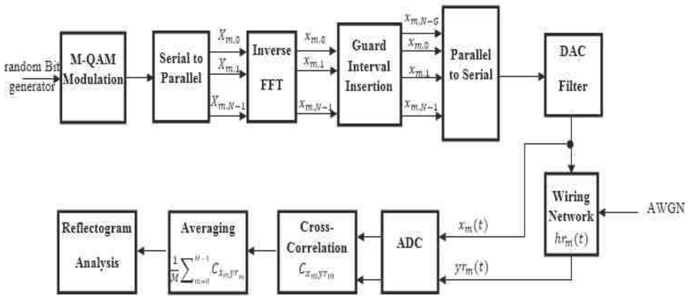

Fig. 2. Diagnosis Block Diagram using OMTDR Method.

Fig.2. The reflectogram is obtained using the inter-correlation function between the injected and reflected signals. Then, an averaging step is performed in order to reduce the undesirable signals and improve the Signal-to-Noise Ratio (SNR).

B. Sensor Communication Function using OMTDR

Thanks to the multi-carrier principle, OMTDR provides sensors communication in order to reduce diagnosis ambiguities due to multi-path propagation in complex wiring networks.

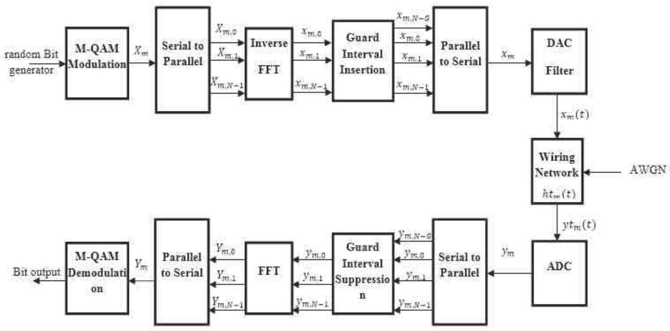

Fig. 3. The Block Diagram of Sensors Communication.

The transmitted signal $ht_{m,i}$ for communication between S_1 and S_2 is expressed as follows:

$$ht_{m,i} = \frac{1}{2\pi} \sum_{i=0}^{N-1} T_{21}(\omega) e^{j\omega i \frac{n}{N}}. \quad (19)$$

The transmission coefficient T_{21} is given by (10). The same formula is used for communication between S_1 and S_3 by replacing T_{21} by T_{31} (given by (11)). At the receiver side, the receiver sensor performs the inverse process of the transmitter [10] (guard interval suppression, FFT, M-QAM Demodulation) as shown by Fig.3.
In order to ensure both diagnosis and communication functions, a resource allocation scheme is required to control the available bandwidth and reduce interferences.

IV. A Resource Allocation Scheme for Sensors

In OMTDR reflectometry, the network bandwidth B is divided into N tones using OFDM modulation. Let's introduce the matrix H with dimension $(K \times N)$ where K and N denote, respectively, the sensors number and available tones. H expresses resource allocation indicators where,

$$h_{k,n} = \begin{cases} 1 & \text{if tone } n \text{ is allocated to sensor } k. \\ 0 & \text{if tone } n \text{ is not allocated to sensor } k. \\ -1 & \text{if tone } n \text{ is in a prohibited bandwith.} \end{cases} \quad (20)$$

Thanks to multi-tone reflectometry, the sensors signals are carefully constructed using a resource allocation scheme to choose frequencies below and above the prohibited bandwidth, used by the target system, for communication and diagnosis. Considering N_p as the number of tones in the prohibited bandwidth, the authorized tones number N_u is expressed as follows $N_u = N - N_p$.

Let's assume that N_{diag} and N_{com} denote the tones number reserved for diagnose and communication respectively, where $N_{diag} = \lceil \alpha N_u \rceil$, $N_{com} = \lceil \beta N_u \rceil$ and $\alpha + \beta = 1$. Here, the proposed strategy imposes that sensor S_1 is responsible for network diagnosis and data communication by injecting periodically a test signal down the network. Then, sensors S_2 and S_3 ensure sensors communication.

Therefore, $N_{diag}(S_1) = N_{diag}$ and $N_{com}(S_i) = \left(\frac{N_{com}}{K}\right)$ tones should be allocated to each sensor $i \in \{1,2,3\}$ for, respectively, diagnosis and communication where $K = 3$ in this work. Then, a resource allocation policy is needed for communication tones as shown by the pseudo code 1.

The same pseudo code is applied for diagnosis tones allocation by replacing $N_{com}(k)$ by $N_{diag}(k)$ and matrix H is inherited from resource allocation phase. However, in this case, $K = 1$ as only the sensor S_1 is allowed to make diagnosis and the pseudo code is applied only by sensor S_1 aiming at avoiding the prohibited bandwidth.

Algorithm 1 Communication Tones Allocation

```
for k = 1 → K do
  j = 1;
  while N_com(k) ≠ 0 do
    if Σ_{k=1}^{K} H_(k,j) ≠ 0 then
      j = j + 1;
    else
      H_{k,j} = 1;
      N_com(k) = N_com(k) − 1
    end if
  end while
end for
```

V. Simulation Results

OMTDR was tested on a Y shaped network (Fig.1) consisting of three transmission lines with different lengths $l_1 = 50m$, $l_2 = 60m$ and $l_3 = 110m$. The total bandwidth in the studied network is equal to $0 - 256$ MHz. For these simulations, the prohibited bandwidth is $64 - 192$ MHz. The characteristic impedance of all transmission lines Z_c is equal to 100Ω. Considering additive white Gaussian noise, the SNR chosen here is equal to $10dB$. Here, the allocation factors α and β are chosen as α=25% and β=75%. Simulation parameters are presented in Table I.

TABLE I
Simulation Parameters

Parameter	Variable	Value
M-QAM modulation	M	4
Number of available tones	N	512
Useful symbol duration(μs)	T_s	224
Guard interval duration(μs)	T_G	28
Tones spacing(MHz)	Δf	0.5

A. Hard Fault Detection: Open Circuit Fault

Let's now consider unmatched transmission lines ($Z_L \neq Z_c$) on the network. Fig.4 shows the reflectogram obtained by sensor S_1 using OMTDR method in a Y shaped network with $Z_L = +\infty$ at the end of lines W_2 and W_3. Here, the proposed method detects and locates accurately the end of the lines W_2 and W_3 by sensor S_1, referred by the positive obtained peaks at $110m$ and $160m$. The first obtained negative peak at $50m$ represents the junction that connects the three lines.

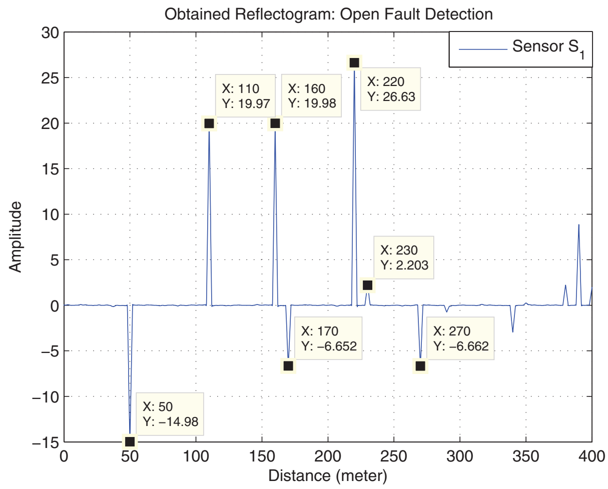

Fig. 4. End of Open Circuit Fault Location using OMTDR by Sensor S_1

B. Soft Fault Detection: Chafing Fault

In order to simulate a soft fault, a local variation of capacitance ΔC and inductance ΔL are simulated on the branch W_2 of the network where $C_d = (1 + \Delta C)\, C$ and $L_d = (1 - \Delta L)\, L$. C_d and L_d represent the fault capacitance and inductance. Fig.5 shows a reflectogram at S_1 with a soft fault where $\Delta C = 50\%$ and $\Delta L = 50\%$. Here, the fault portion is located at $70m$ from S_1 as shown by the very weak peak at that distance. The other weak peaks for example $130m$, $150m$, $180m$, represent the same detected soft fault as the first peak but shifted in time due to round-trips in the network. Fig.6 shows the soft fault peak variations in terms of fault

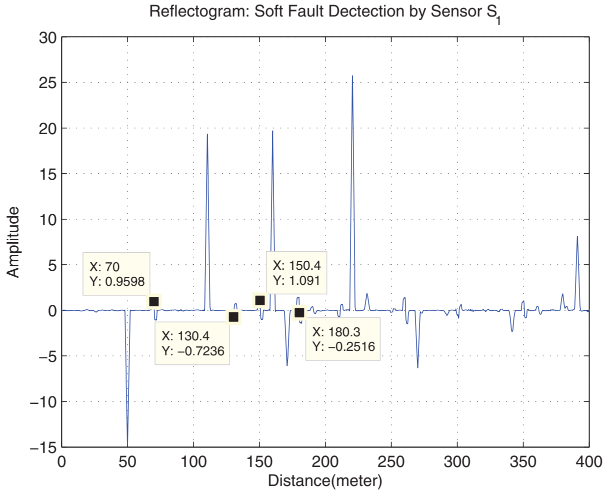

Fig. 5. Soft Fault Detection using OMTDR by Sensor S_1

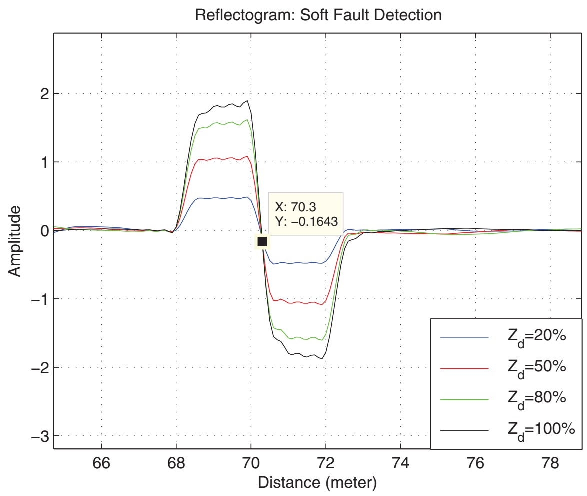

Fig. 6. Soft Fault Peak Variation for Different Fault Impedance Values

impedance variation (Z_d) relative to the network characteristic impedance Z_c. For a low ΔZ_d, the corresponding very weak pic may be indistinct on a reflectogram. Then, we need an additional information for ambiguities cancellation.

C. Sensors Communication

The Bit Error Rate (BER) is a key parameter used to characterise the communication channel quality. It represents the number of bit errors divided by the total number of transmitted bits during a given time interval.

Fig.7 shows the BER variation in terms of fault impedance (Z_d) variation relative to the characteristic impedance for different SNR values. Here, the BER increases when the fault severity increases. In our case ($SNR = 10dB$), the BER values for communication from S_1 to S_2 and S_1 to S_3 are given in Table II. Referring to Fig.7, the $BER(S_1, S_2)$ corresponds to a healthy link between S_1 and S_2 ($\Delta Z_d = 0$).

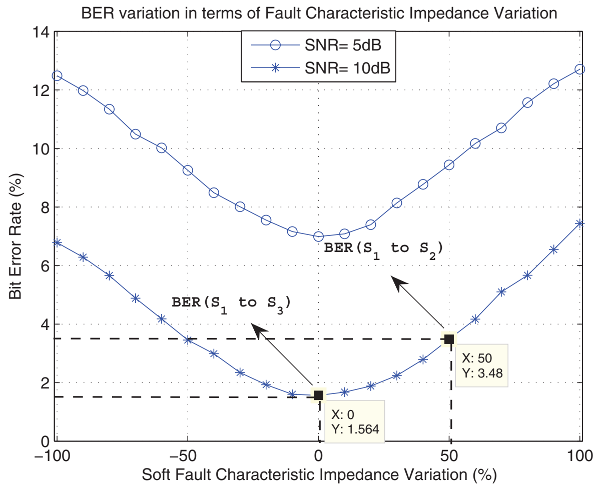

Fig. 7. Sensors Communication: BER performance

TABLE II
OBTAINED BER VALUES

Communication	(S_1,S_2)	(S_1,S_3)
BER	1.56%	3.48%

However, when $BER(S_1, S_3) = 3.48\%$, ΔZ_d is equal to 50%, indicating a soft fault on link S_1 to S_3. Thus, sensors communication permits to give an additional information on the network quality and removes ambiguities caused by small faults.

D. Fault Localisation using Bayesian Networks

After network diagnosis and sensors communication, sensor S_1 is responsible for decision making about the network state and the position of likely detected faults. To determine the confidence level to be allocated in the results provided by this sensor, a probabilistic approach is used. It is based on the Bayesian Networks (BN) [14], [15]. Here, the variables of interest are defined in Table III.

In this case, nodes of the BN are divided into two sets:

TABLE III
VARIABLES OF INTEREST

Variable	Notation	Description	Modality
Wire1	X_1	Wire W_1	Faulty/Healthy
Wire2	X_2	Wire W_2	Faulty/Healthy
Wire3	X_3	Wire W_3	Faulty/Healthy
PeakS1	Obs_1	Peak Detection	Yes/No
DistS1	Obs_2	Peak Distance to S_1	Inf50m/Sup50m
BERS1toS2	Obs_3	BER (S_1 to S_2)	Inf1point6/Sup1point6
BERS1toS3	Obs_4	BER (S_1 to S_3)	Inf1point6/Sup1point6

- χ is the set of nodes representing the real state of the studied system.
- χ_o is the set of nodes representing the observed symptoms of the studied system.

Considering $\chi_o = \{Obs_1, Obs_2, Obs_3, Obs_4\}$ and $\chi = \{X_1, X_2, X_3\}$, the conditional probability for faults on branch W_1,W_2 or W_3 is, respectively, given by:

$$P(X_1/Obs_1, Obs_2) = \frac{P(X_1; Obs_1, Obs_2)}{P(Obs_1, Obs_2)}. \quad (21)$$

$$P(X_2/Obs_1, Obs_2, Obs_3) = \frac{P(X_2; Obs_1, Obs_2, Obs_3)}{P(Obs_1, Obs_2, Obs_3)}. \quad (22)$$

$$P(X_3/Obs_1, Obs_2, Obs_4) = \frac{P(X_3; Obs_1, Obs_2, Obs_4)}{P(Obs_1, Obs_2, Obs_4)}. \quad (23)$$

As expressed by equation (21), BER is not considered for fault localisation on branch W_1. Here, the peak presence (PeakS1) and distance (DistS1) are sufficient because if DistS1="Inf50m", then there is no doubt about the fault presence on wire W_1. The BN is modelled as shown by Fig. 8. For fault localisation, the BN is powered by the collected

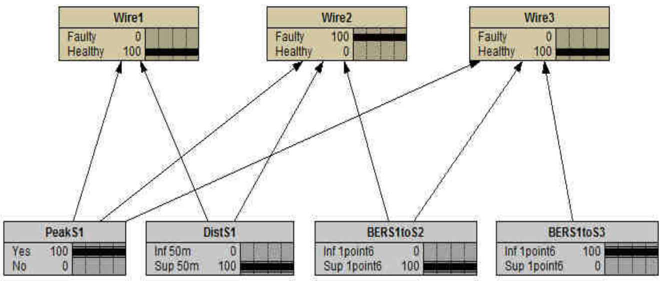

Fig. 8. The Bayesian Network Structure

information about the peaks (presence and distance relative to S_1) and obtained BER values. Then, these information are propagating in the BN to compute conditional probability for fault presence on branch W_1, W_2 or W_3. In this case, simulation results are presented in Table IV. Based on the

TABLE IV
FAULT LOCALISATION

Observed symptom Probability	Real State Result Probability
$P(Obs_1 =$'Yes'$)$=100% $P(Obs_2 =$'Sup50m'$)$=100 % $P(Obs_3 =$'Sup1point6'$)$=100% $P(Obs_4 =$'Inf1point6'$)$=100%	$P(X_1/Obs_1, Obs_2 =$'Healthy'$)$=100% $P(X_2/\chi_o - \{Obs_4\} =$'Faulty'$)$=100% $P(X_3/\chi_o - \{Obs_3\} =$'Healthy'$)$=100%

BN results, the fault is present on branch W_2 with certainty $(Pr(X2/Obs_1, Obs_2, Obs_3) = 100\%)$.

E. Discussion and Perspectives

Simulation results show that the proposed OMTDR method performs well in a branched wiring network. It permits not only to detect faults even with the presence of noise, but also to locate them with no ambiguities thanks to the communication between sensors. Here, only one sensor has to inject signal test for fault diagnosis, thus reducing the diagnosis process complexity. In this case, the BN seems to be not interesting as it provides a deterministic confidence level (equals to 100%). However, it is more important considering other parameters (sensor reliability, wires environment, etc.) which may increase the decision uncertainty. This is the purpose of future works.

VI. CONCLUSION

A new reflectometry method called OMTDR is proposed. Here, a test signal is constructed using OFDM principle. This test signal is sent down the wiring network and the received signal is examined to retrieve information regarding potential defects in the network while the target system is on-line. A communication function is introduced for sensors in order to reduce ambiguities caused by signals propagation and then improve location accuracy in complex networks. The proposed OMTDR was simulated in a branched wiring network and shown to work effectively. This work will be applied to more complicated network topologies, tested experimentally and then implemented in embedded systems as future works.

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