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On-Line Diagnosis using Orthogonal Multi-Tone Time Domain Reflectometry in a Lossy Cable

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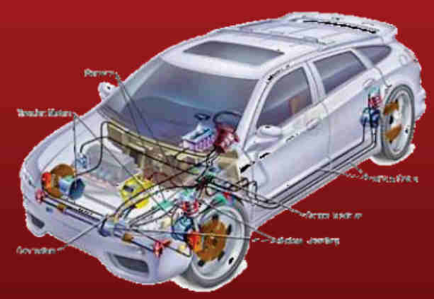
Context & Motivation

Context:

- Embedded electronic explosion.
- Embedded systems complexity increase.
- «**X-by-wire**» technology appearance.



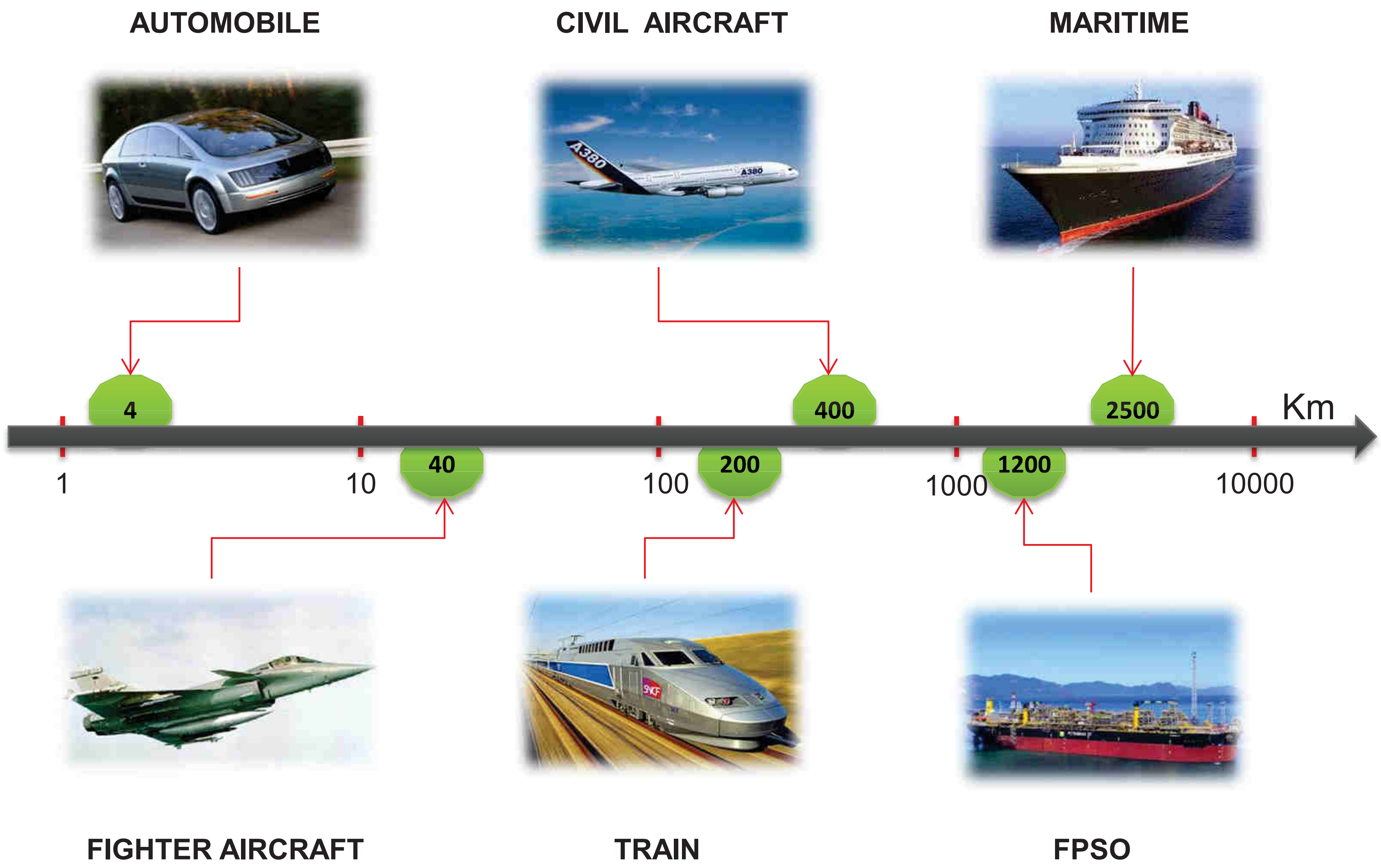
Motivations:

- Cable length increase.
- Connections number increase.
- Faults number caused by cables increase.

Solution, interest & advantages:

- Solution: wiring networks diagnosis system.
- Interest: detect, locate and characterize faults.
- Advantages: maintenance cost reduction (time, resources, etc.), system reliability increase, etc.

Context & Motivation



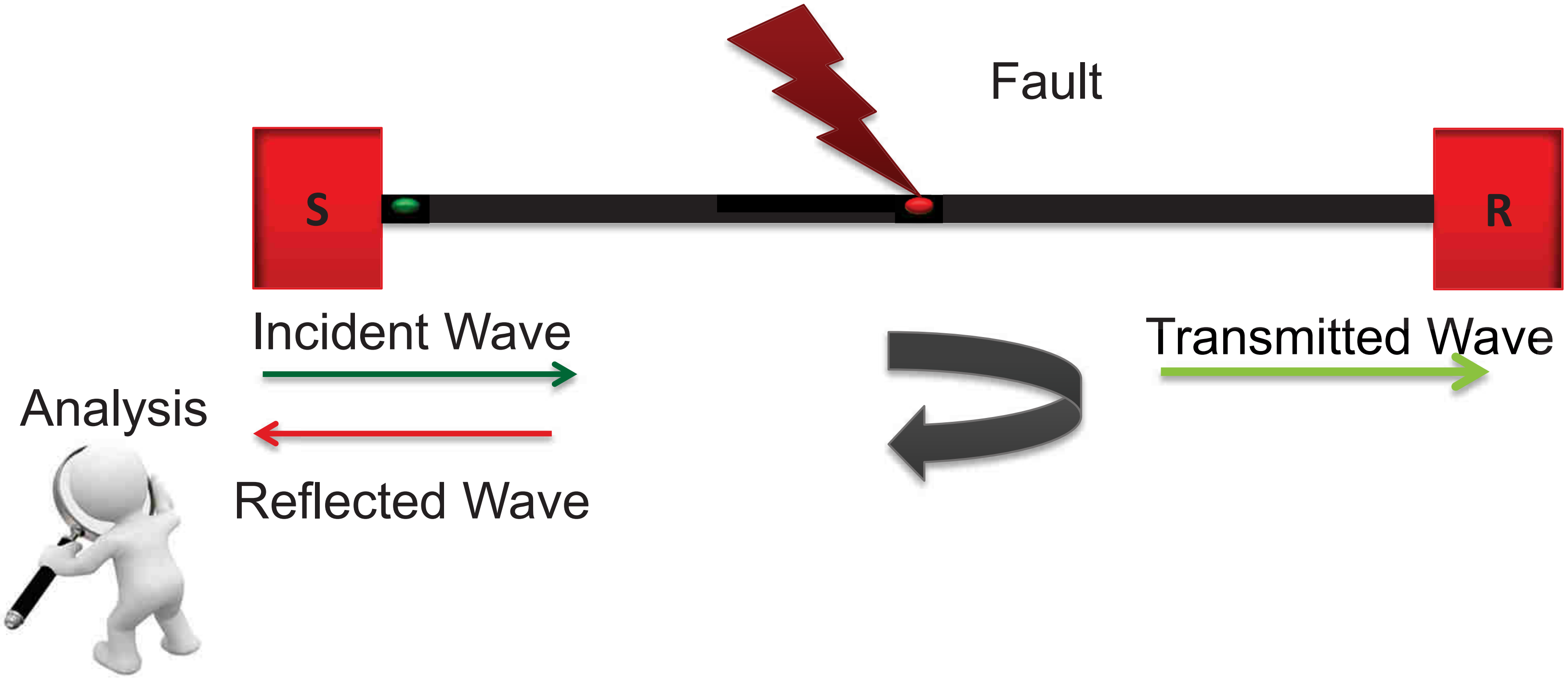
Cumulative Cables Length in the Transport Field

State of the Art & Questions (1/2)

Reflectometry:

- A wideband test signal is injected down the wire. During its propagation, a part of its energy reflects back to the injection port when it crosses impedance discontinuities.

- The analysis of the received signals, called “reflectogram”, gives information about the wire faults (presence, position, type).



State of the Art & Questions (2/2)

TDR*: Time Domain Reflectometry*

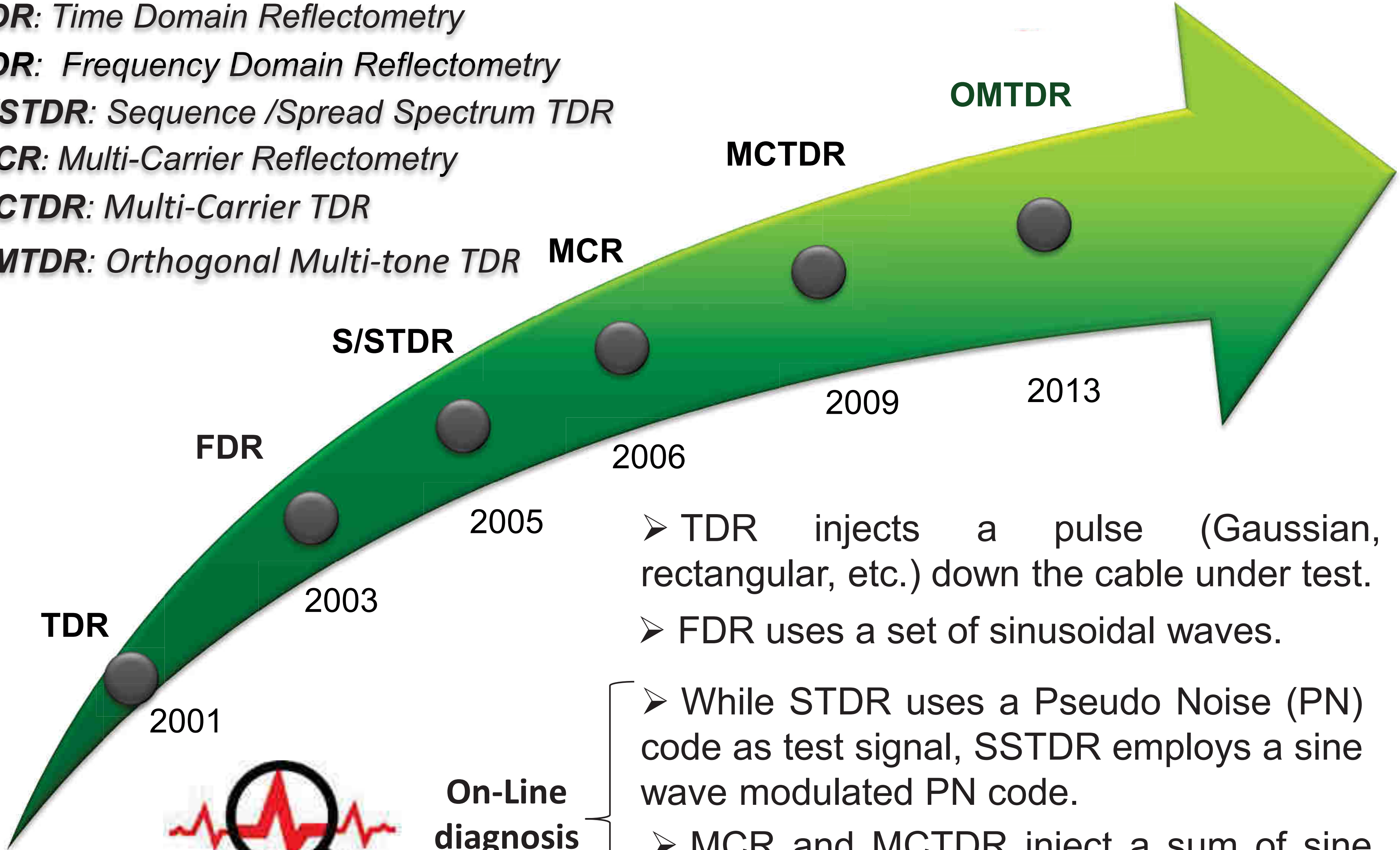
FDR*: Frequency Domain Reflectometry*

S/STDR*: Sequence /Spread Spectrum TDR*

MCR*: Multi-Carrier Reflectometry*

MCTDR*: Multi-Carrier TDR*

OMTDR*: Orthogonal Multi-tone TDR*



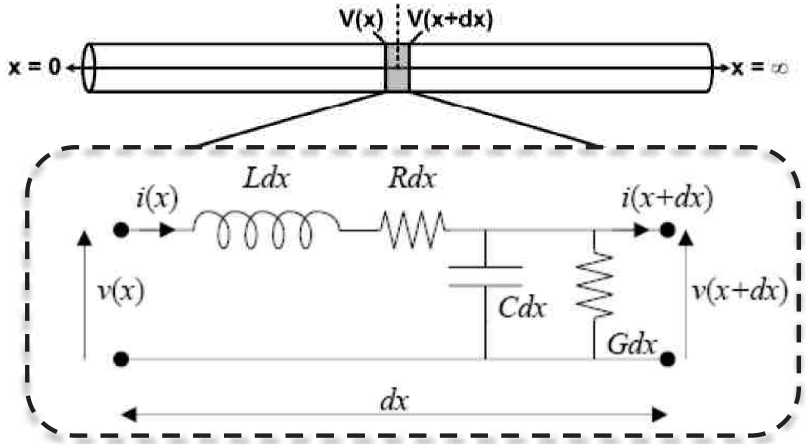
- ➢ TDR injects a pulse (Gaussian, rectangular, etc.) down the cable under test.
- ➢ FDR uses a set of sinusoidal waves.

On-Line diagnosis

- ➢ While STDR uses a Pseudo Noise (PN) code as test signal, SSTDR employs a sine wave modulated PN code.
- ➢ MCR and MCTDR inject a sum of sine waves using Inverse Digital Fourier Transform (IDFT).

Wave propagation Model in a cable

RLCG Propagation Model:



R: Resistance
L: Inductance
C: Capacity
G: Condutance

Telegrapher's equations:

$$\begin{cases} \frac{\partial v(x,t)}{\partial x} = -R \cdot i(x,t) - L\frac{\partial i(x,t)}{\partial t} \\ \frac{\partial i(x,t)}{\partial x} = -G \cdot v(x,t) - C \cdot \frac{\partial v(x,t)}{\partial t} \end{cases}$$

Propagation constant:

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

Characteristic impedance:

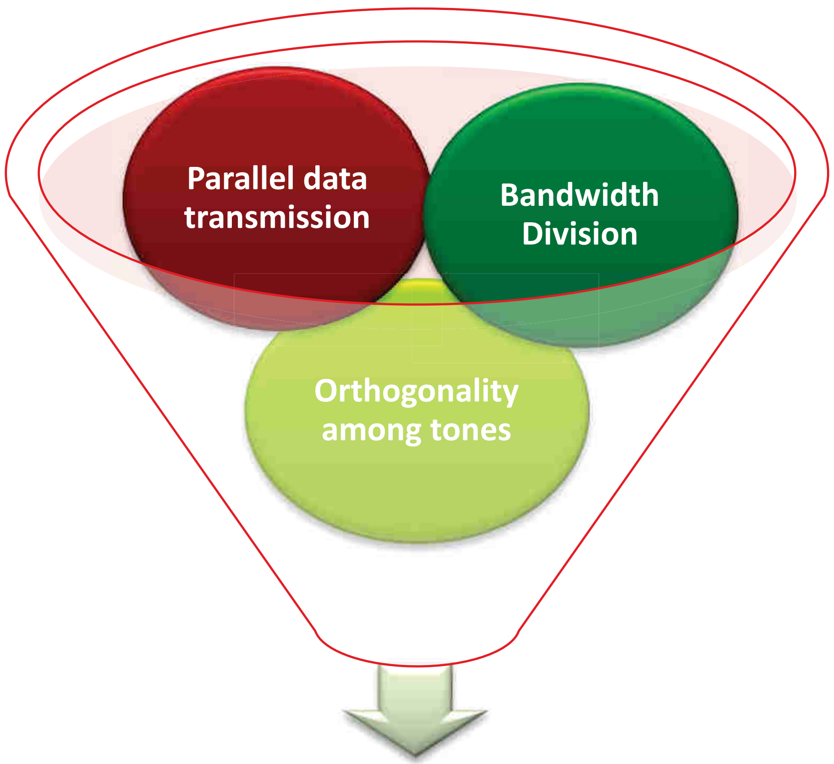
$$Z_c(\omega) = \sqrt{(R + jL\omega)/(G + jC\omega)}$$

Angular Frequency:

$$\omega = 2\pi f$$

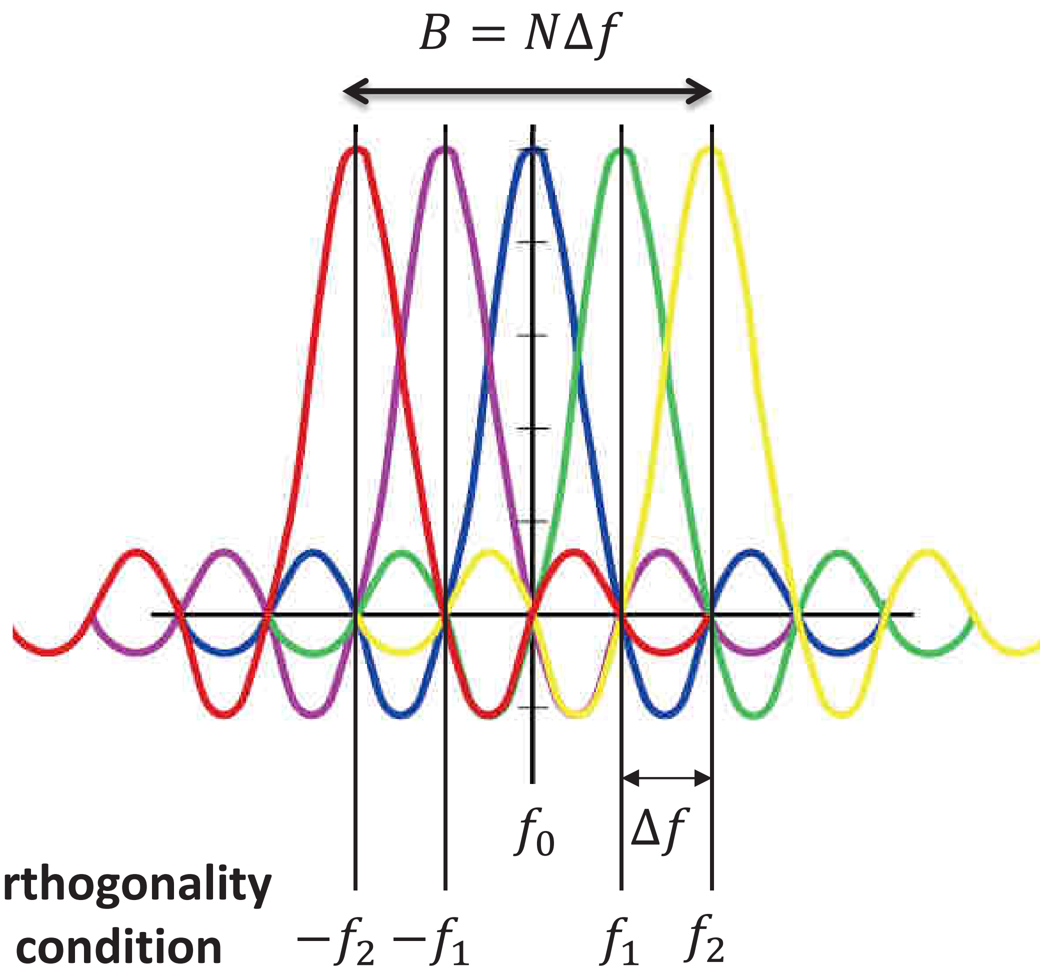
OMTDR: Motivation

OMTDR= Orthogonal Multi-Tone Time Domain Reflectometry



Total Bandwidth Control
Data Rate Increase
Spectral Efficiency
Interference Avoidance

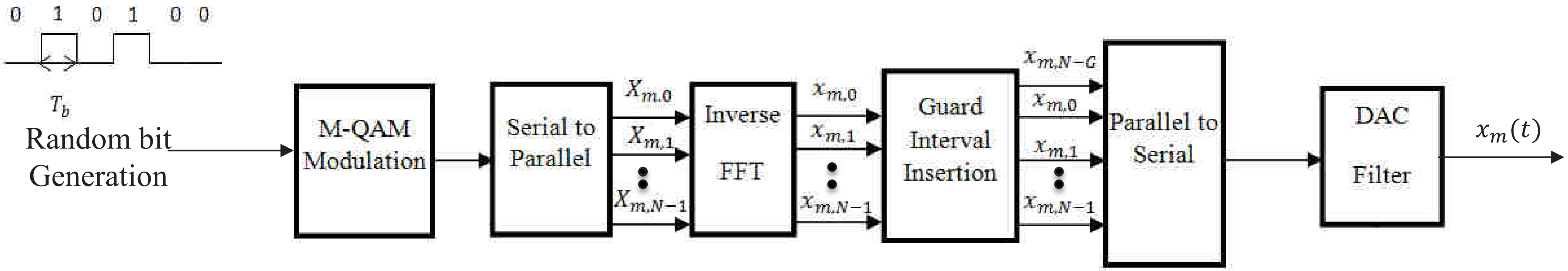
Frequency Spectrum of N Tones

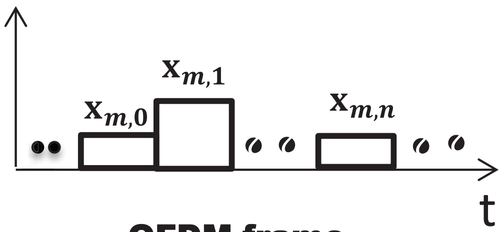


Orthogonality condition

$\Delta f = 1/T_s$ T_s=OFDM symbol duration

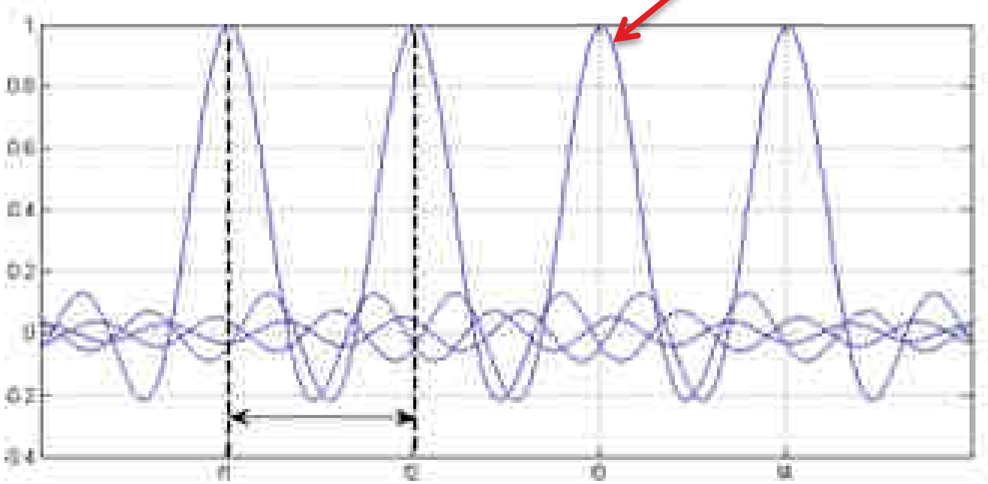
OMTDR: Signal Generation





OFDM frame

- The n^{th} tone is expressed as:
  - Time domain: $g_n(t) = \begin{cases} e^{j2\pi n\Delta f t} & \text{if } \forall t \in [-T_G, T_s] \\ 0 & \text{if } \forall t \notin [-T_G, T_s] \end{cases}$
  - Frequency domain: $G_n(f) = T\, sinc(\pi T\,(f - n\Delta f))$



Parameter	Definition
T_s	Useful OFDM symbol duration
T_G	Guard interval duration
$T = T_s + T_G$	Total OFDM symbol duration
Δf	Frequency spacing among consecutive tones

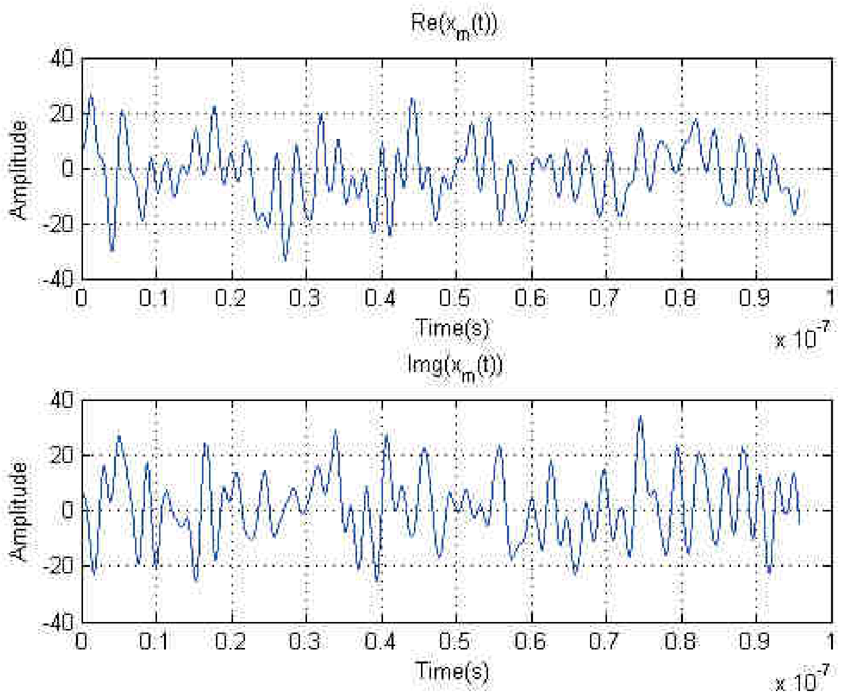
OMTDR: Signal Generation

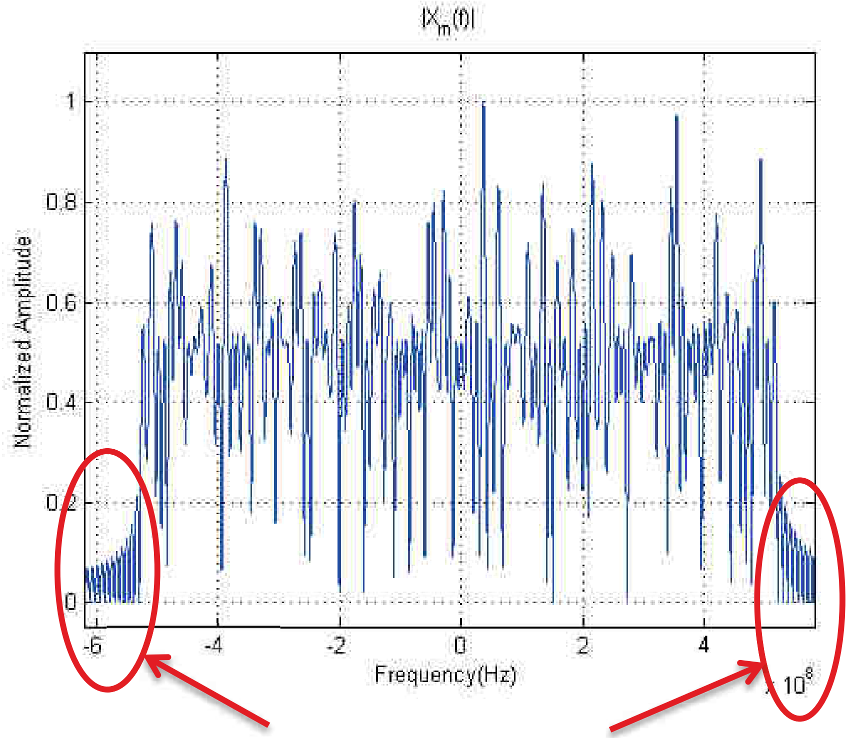
- The baseband OFDM signals is written as:
  - **Time domain:**

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

  - **Frequency domain:**

$$X_m(f) = T \sum_{n=0}^{N-1} X_{m,n} sinc(\pi T(f - n\Delta f))$$





unlimited spectrum
(*sinc*)

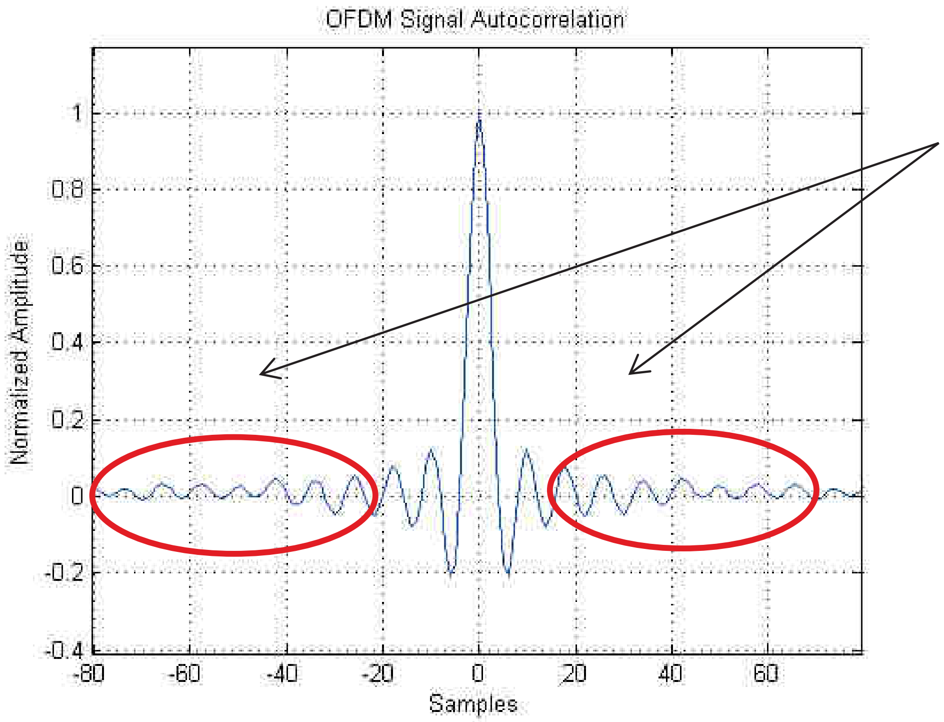
OMTDR: Signal Generation

- In discrete domain, the sample of OFDM signal is:

$$x_{m,i} = \sum_{n=0}^{N-1} X_{m,n} e^{j2\pi i \frac{n}{N}}, i = 0, \cdots, N-1$$

- The OFDM signal autocorrelation is:

$$C_{x_m,x_m}(\tau) = \sum_{i=0}^{N-1} x_{m,i} x^*_{m,i-\tau} = N \sum_{n=0}^{N-1} |X_{m,n}|^2 e^{j2\pi \frac{\tau n}{N}}$$



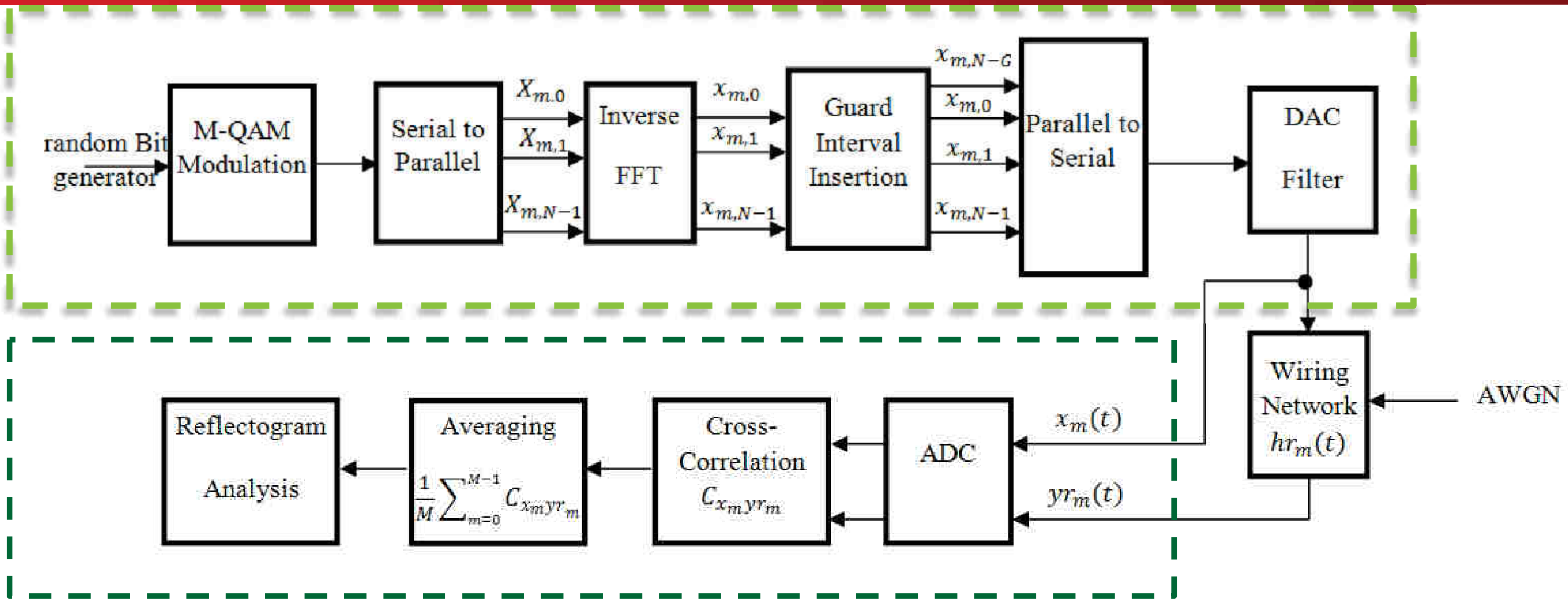
Problem of side lobes: unsuitable for reflectometry diagnosis

Solution: use butterworth filter with frequency-cut equal to 1/T

OMTDR: Diagnosis

Signal Test Injection

Reflected Signal processing



Diagnosis Block Diagram

- ❑ The received signal : $y_{m,i} = hr_{m,i} * x_{m,i} + n_{m,i}$
- ❑ The measured reflected signal:

$$hr_{m,i} = \frac{1}{2\pi} \sum_{i=0}^{N-1} \Gamma_0(\omega) e^{j\omega i \frac{n}{N}}$$

reflection coefficient

$$\Gamma_0(\omega) = \frac{Z_0(\omega) - Z_c}{Z_0(\omega) + Z_c}$$

$$Z_0(\omega) = \frac{AZ_l(\omega) + B}{CZ_l(\omega) + D}$$

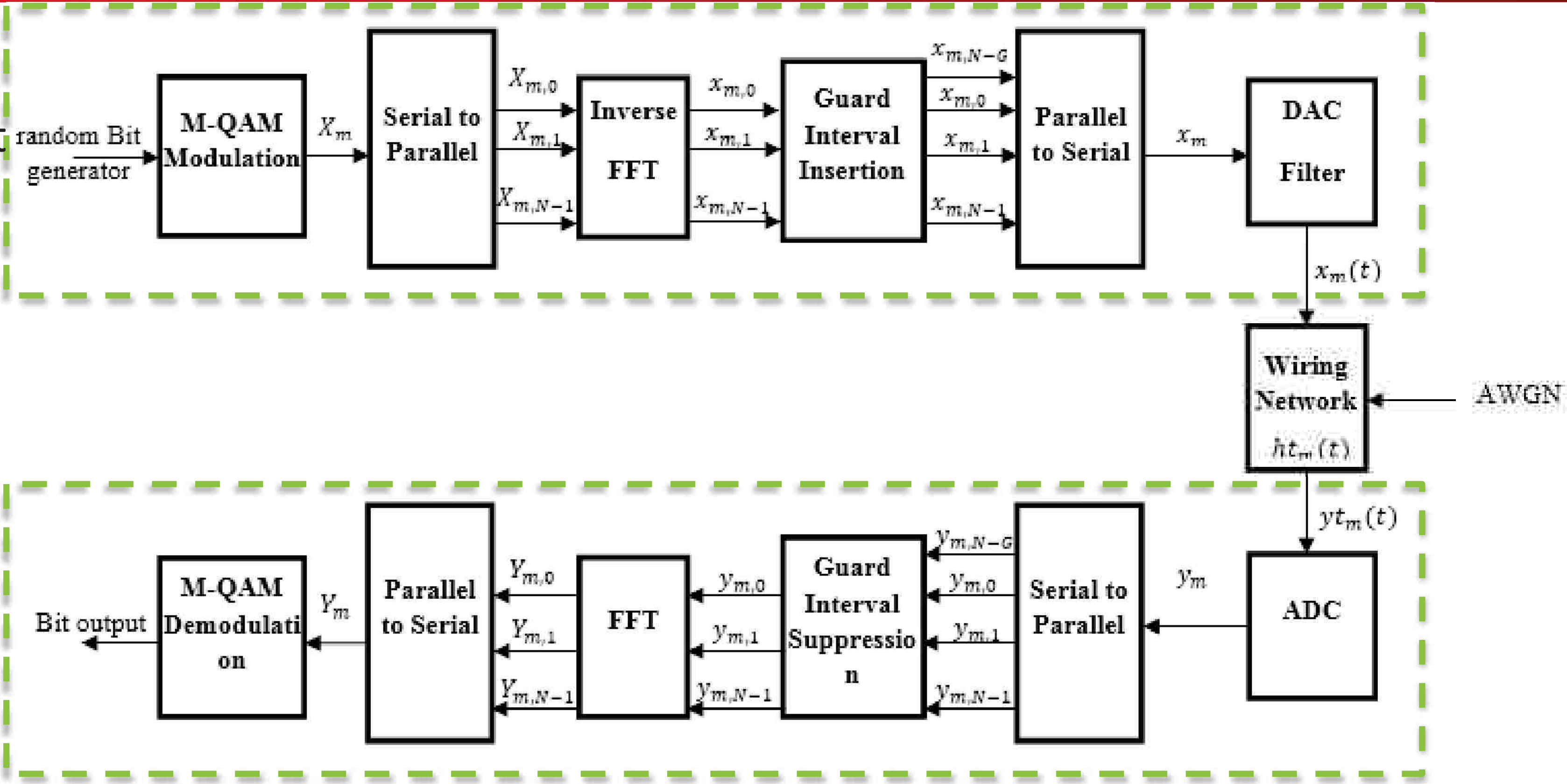
Load at the extremity

Injection port

OMTDR: Communication

Signal Test Injection

Signal Reception



- The transmitted signal:

$$ht_{m,i} = \frac{1}{2\pi} \sum_{i=0}^{N-1} T_0(\omega) e^{j\omega i \frac{n}{N}}$$

Transmission coefficient

$$T_0(\omega) = \frac{2}{A + B/Z_c(\omega) + CZ_c(\omega) + D}$$

Resource Allocation Policy

N: Number of tones

K: Number of sensors

$N_{diag}(k)$: Number of tones for sensor k

H(KxN): Allocation Matrix

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

Algorithm 1 Tones Allocation

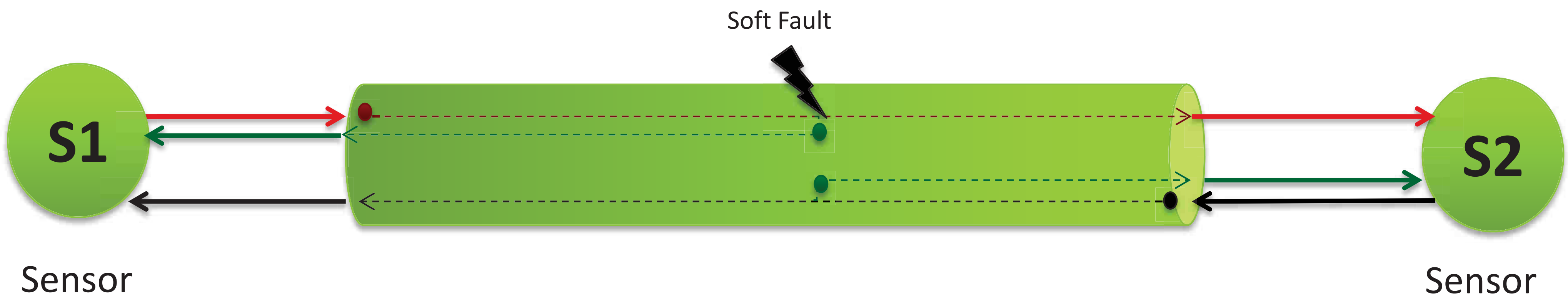
```
for k = 1 → K do
    j = 1;
    while N_diag(k) ≠ 0 do
        if Σ_{k=1}^{K} H_(k,j) ≠ 0 then
            j = j + 1;
        else
            H_{k,j} = 1;
            N_diag(k) = N_diag(k) − 1
        end if
    end while
end for
```

The coefficient $X_{m,n}$ permits to control the signal Spectrum as:

$$X_{m,n} = 0 \Rightarrow X_m(f) = 0 \forall f \in \{f \in \Re^+ : \exists n \in [0, N-1], \forall f = n\Delta f\}$$

Simulation Results: Lossy Cable

Study Network: Transmission Line

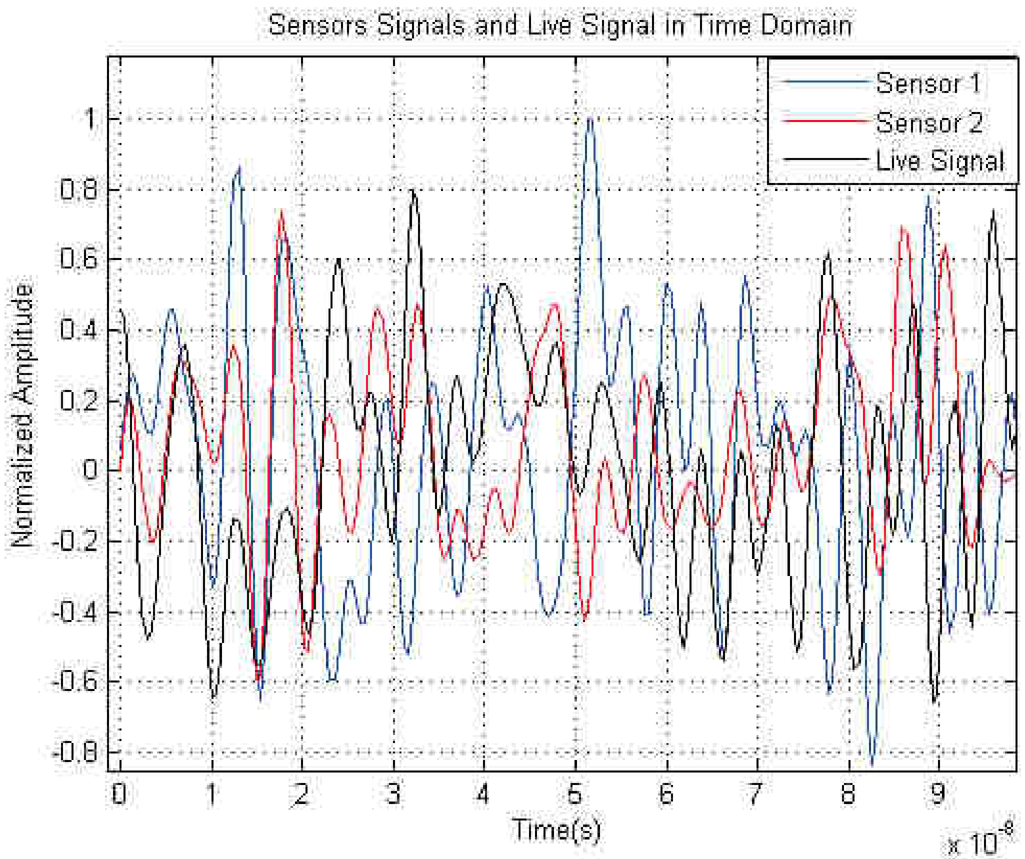


Parameter	Notation	Value
Cable length	L	100m
Total Bandwidth	B	0 MHz – 256 MHz
Prohibited Bandwith		64 MHz – 192 MHz
Characteristic Impedance	Z_c	50 Ω
Number of Tones	N	512
Tones spacing	Δf	0.5 MHz
Useful symbol duration	T_u	224 µs
Guard Interval duration	T_G	28 µs

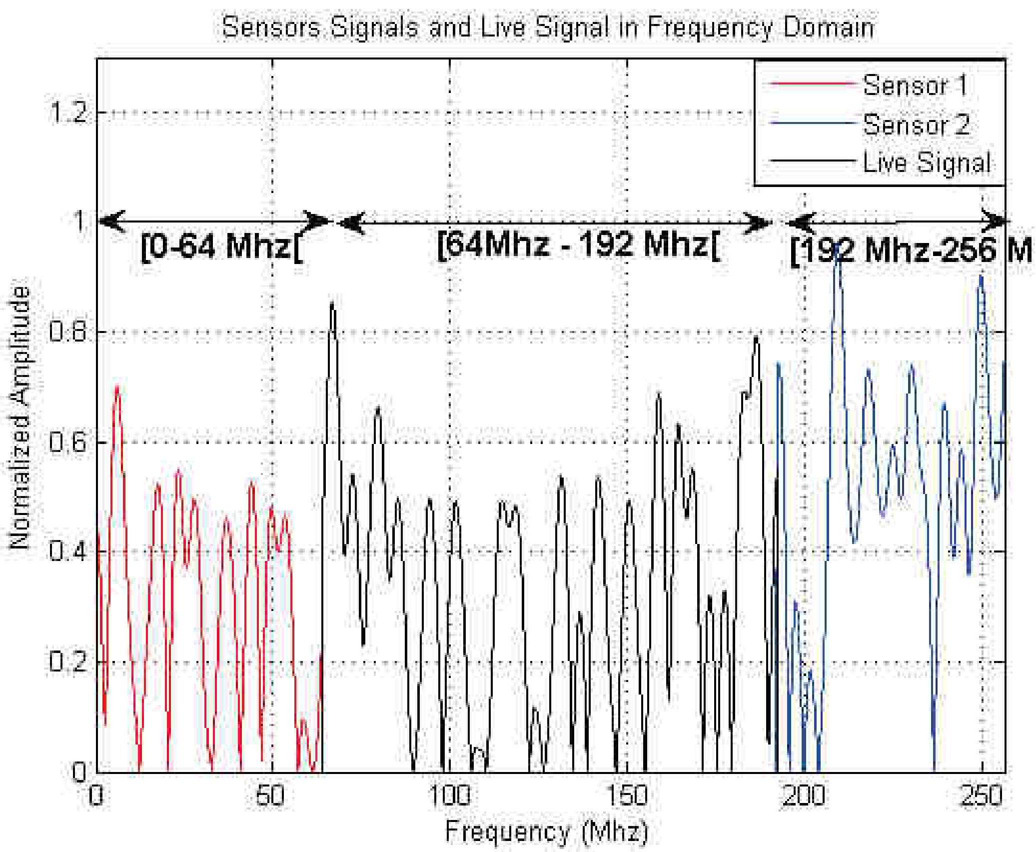
Simulation Results: Lossy Cable

Tones Allocation for Sensors S1 *and* S2

Time Domain



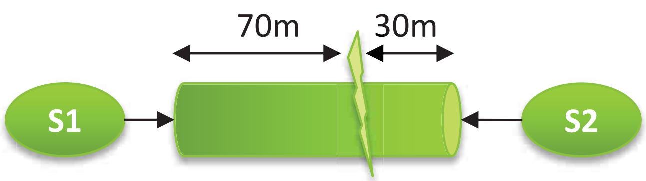
Frequency Domain

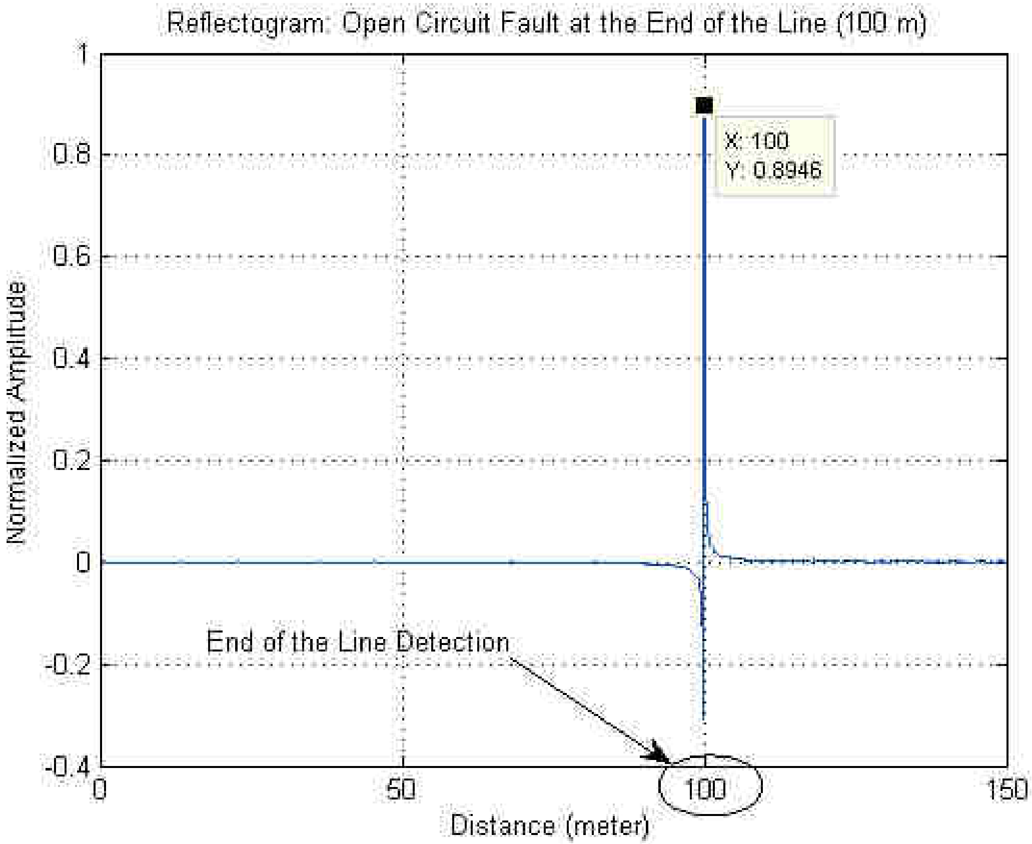


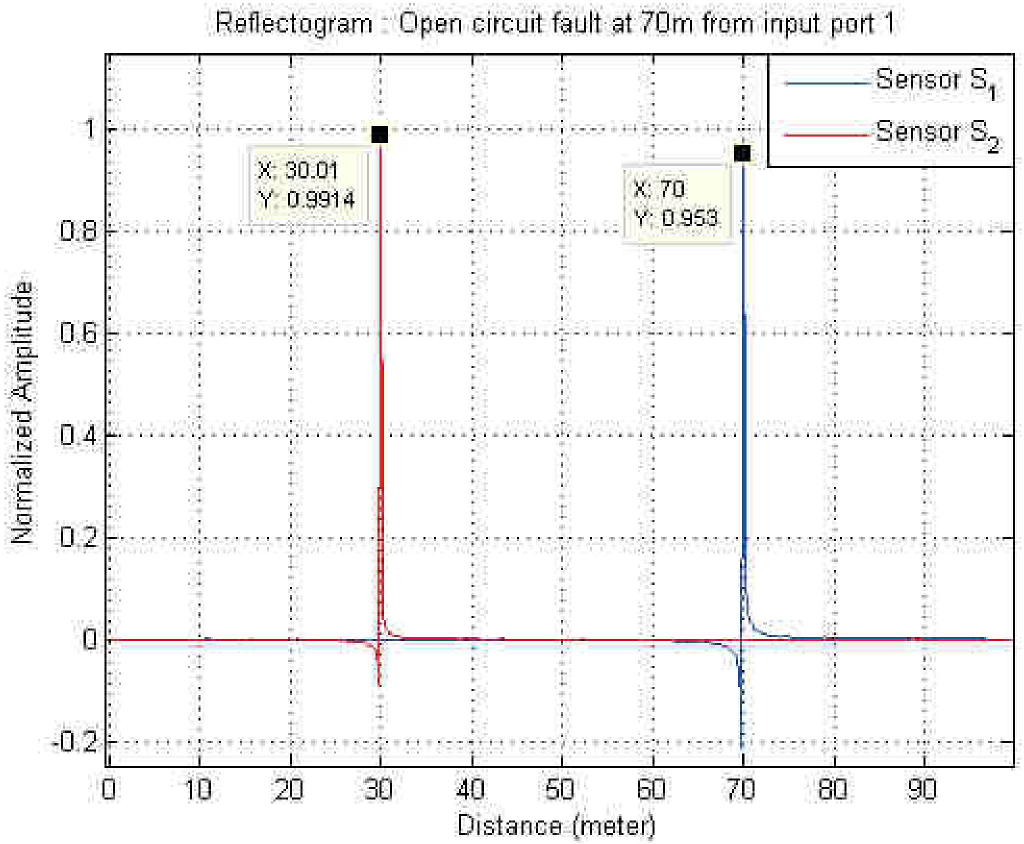
Simulation Results: Lossy Cable

End of Line Detection

Hard Fault Detection: Open Circuit

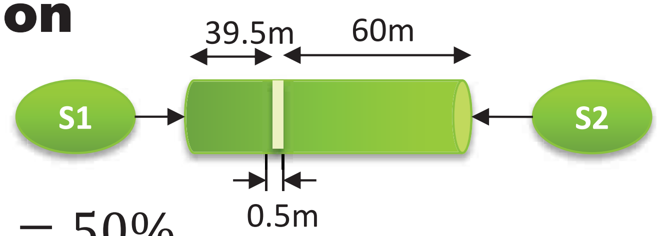






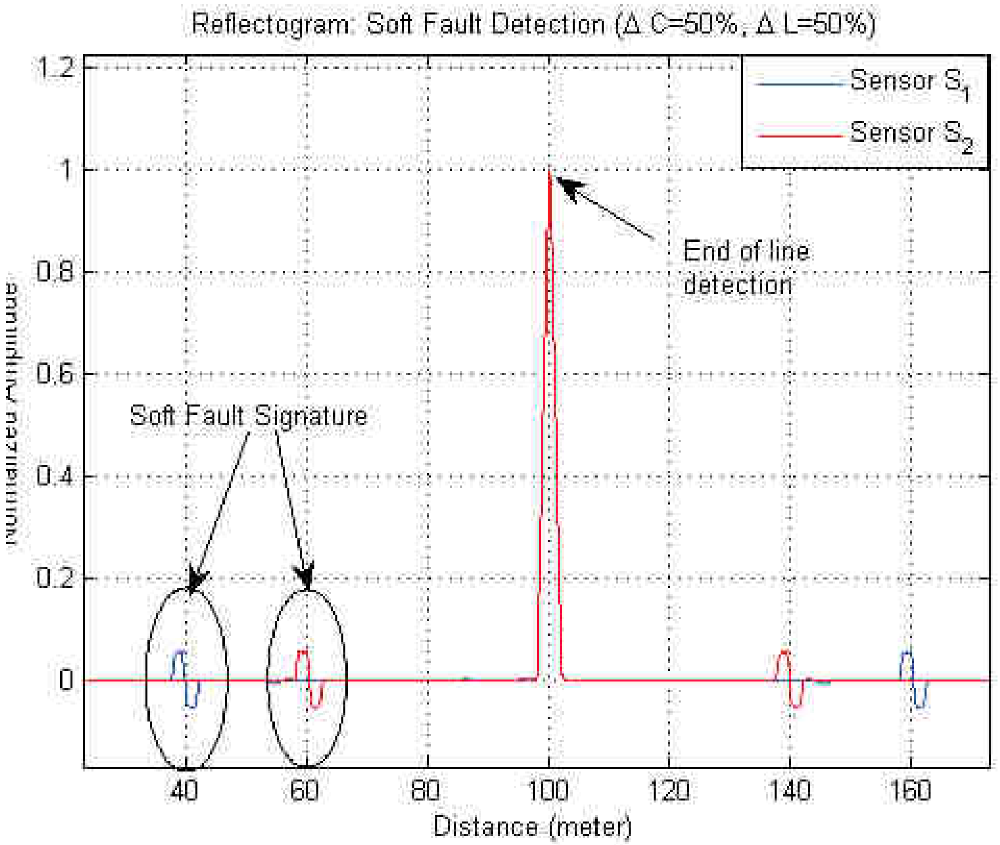
Simulation Results: Lossy Cable

Soft Fault Detection

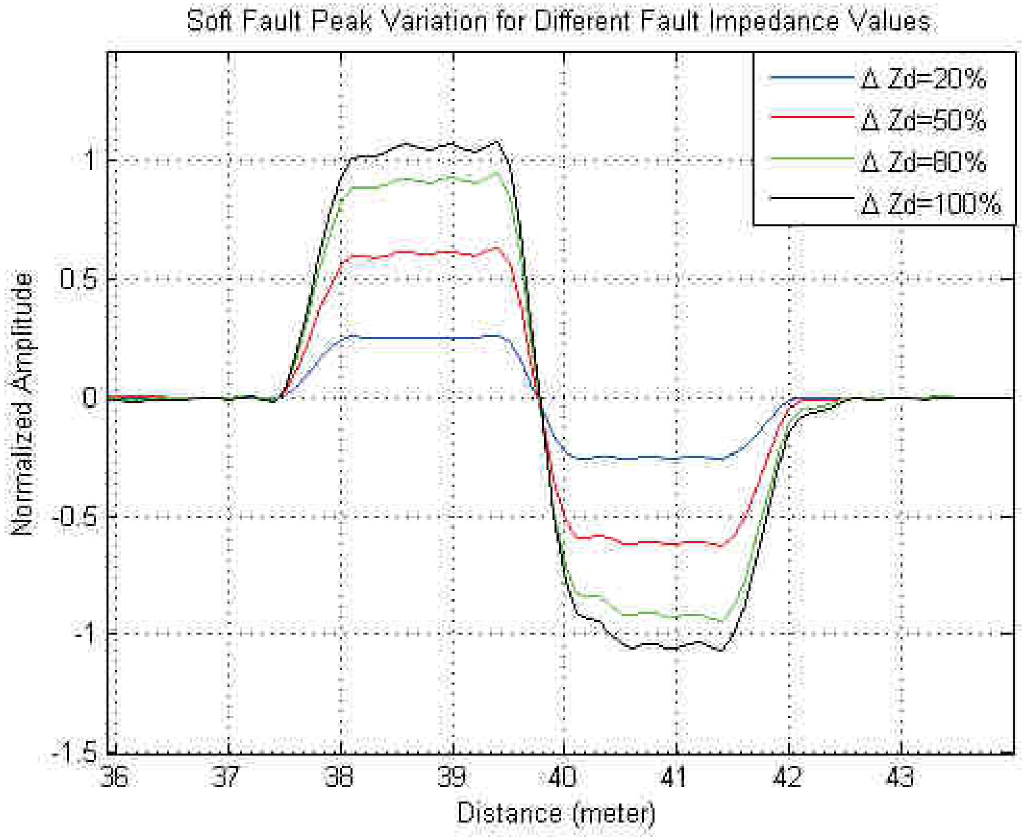


Capacitance variation $\Delta C = 50\%$

Inductance variation $\Delta L = 50\%$



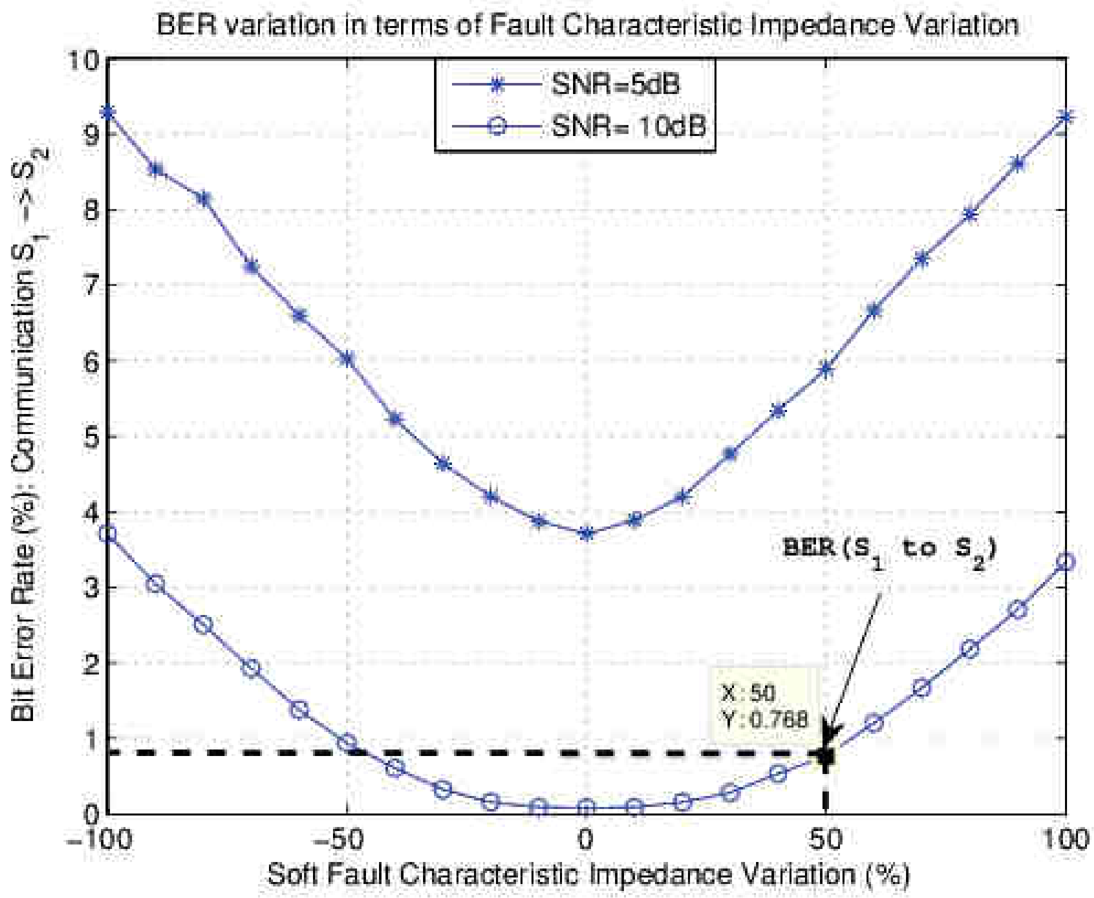
Soft Fault variation



Simulation Results: Lossy Cable

Communication among sensors

Matching between sensor and cable to avoid signal reflection

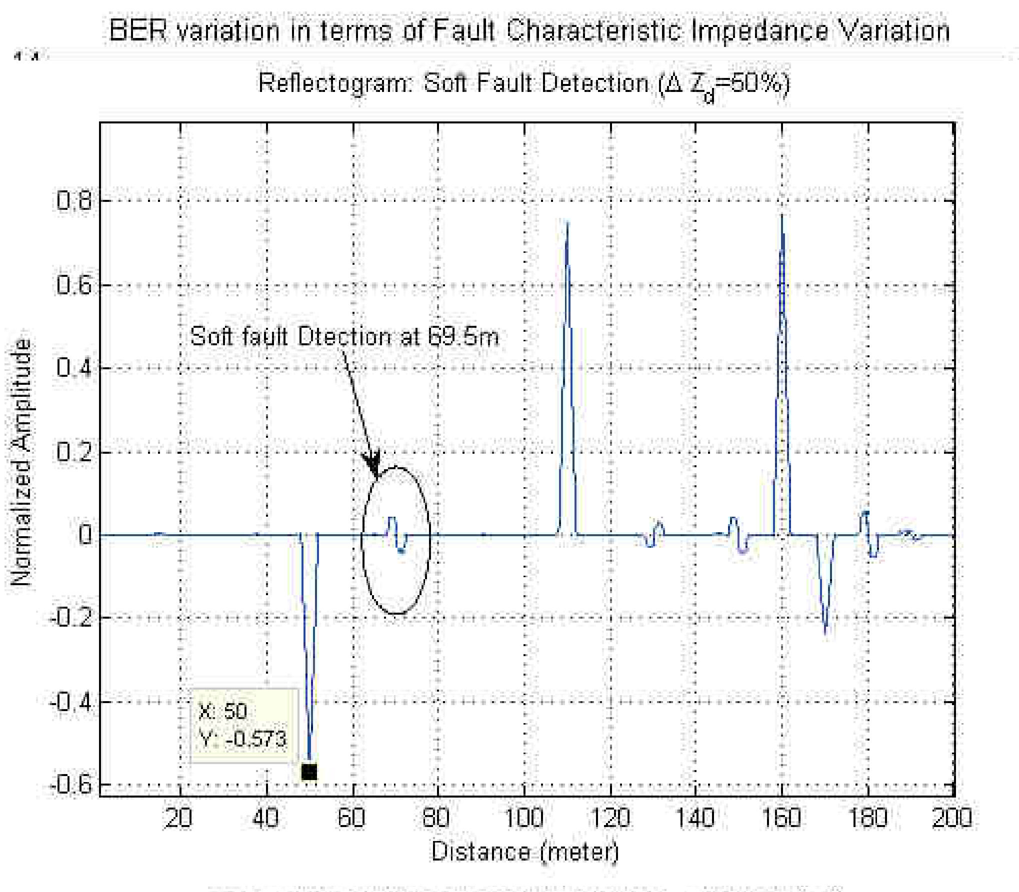


BER increases when the fault severity increases

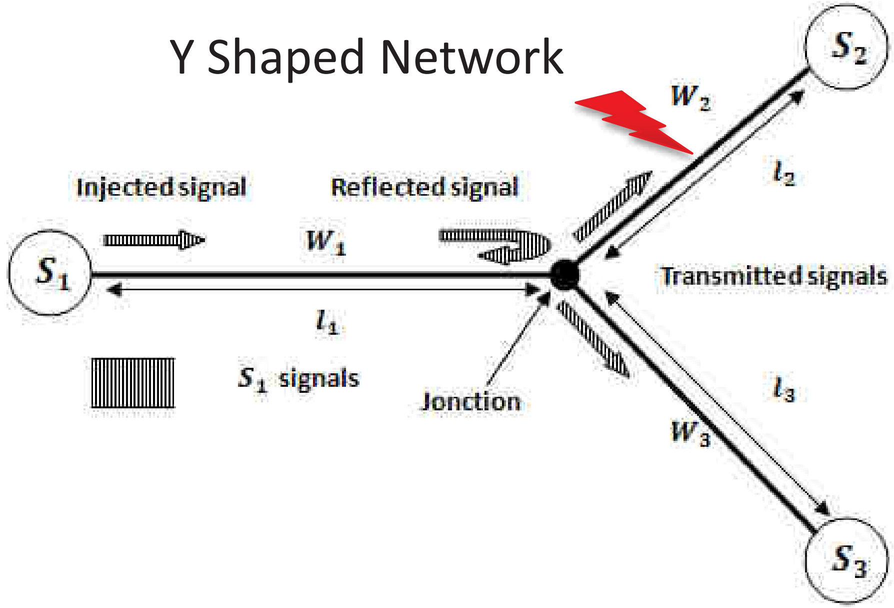
Communication gives an additional information for decision making about the cable state

Simulation Results: Y Shaped Network

Communication among sensors



Y Shaped Network



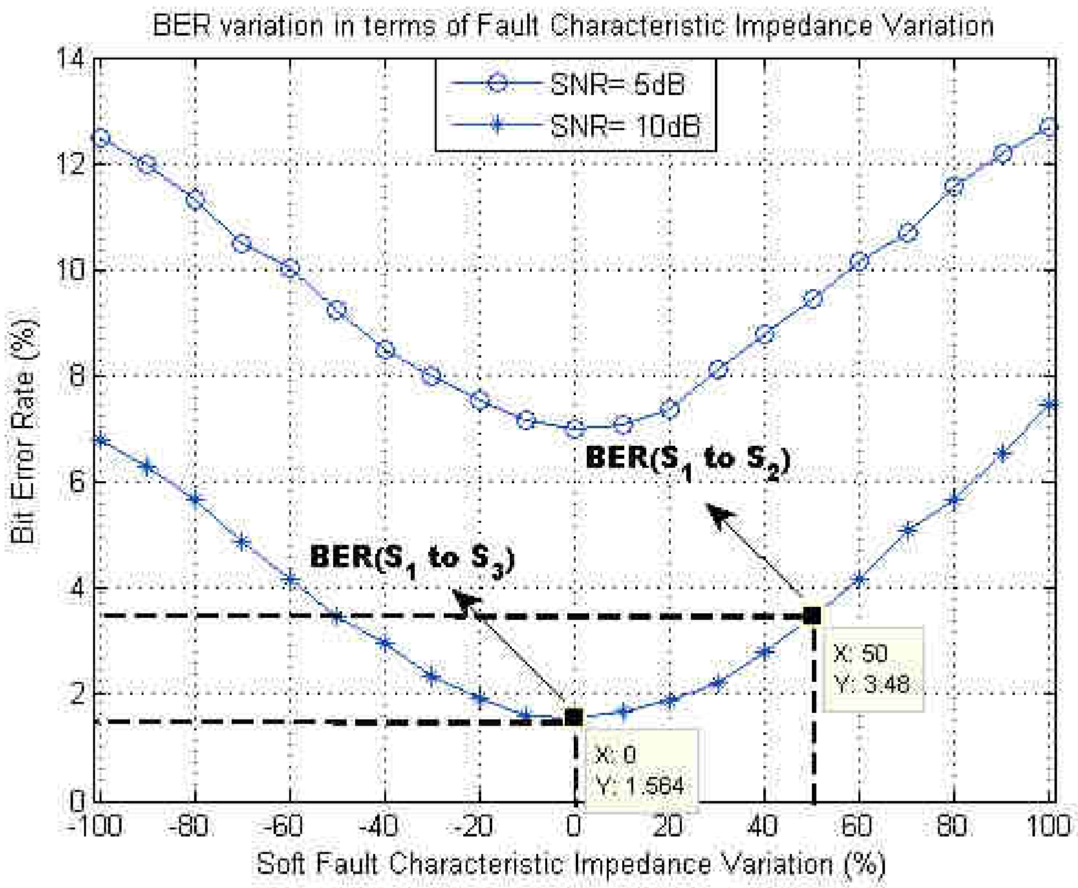
l_1=50 m l_2=60 m l_3=110 m

Soft fault at 19.5m from junction

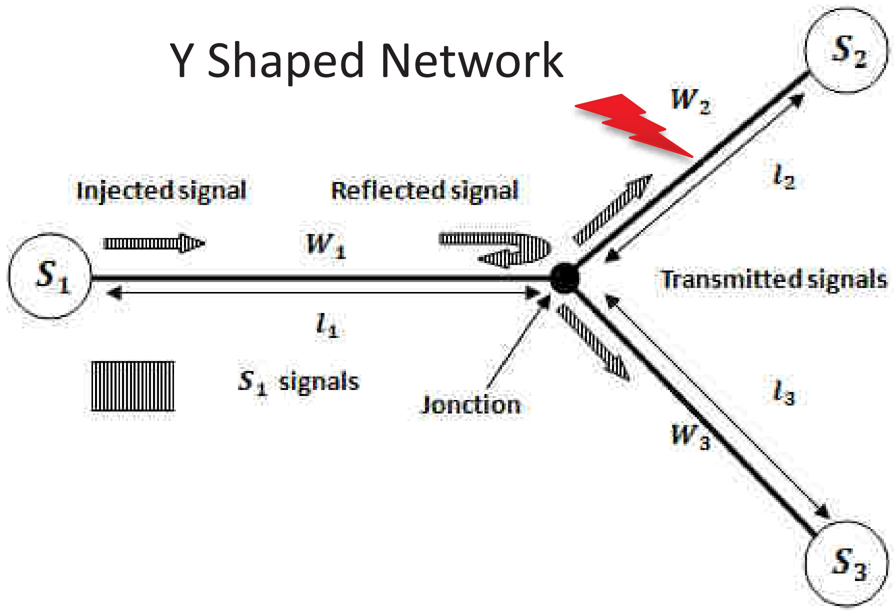
Fault on line W_2 or W_3?

Simulation Results: Y Shaped Network

Communication among sensors



Y Shaped Network



l_1=50 m l_2=60 m l_3=110 m

BER($S_1 to\ S_2$)> BER($S_1 to\ S_3$)

Fault on line W_2

Conclusion & Perspectives

OMTDR: **O**rthogonal **M**ulti-Tone **T**ime **D**omain **R**eflectometry

Ensures on-line diagnosis.

Improves soft faults detection.

Ensures communication among senors to avoid faults localisation ambiguities

Future Works:

OMTDR will be tested on more complex wiring networks.

OMTDR will be implemented in an electronic card (embedded environment).

Thanks for your attention

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