Fault detection in the DC bus of a vehicle

by

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Submitted to the Department of Electrical Engineering, Electronics,
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Abstract

In this thesis, the topic of fault detection in the DC and communication buses of a vehicle was addressed. Typical fault detection methods were examined and the most appropriate one for the automotive DC bus was further investigated. More techniques commonly used in aviation are investigated and compared. A Matlab Simulink simulation model for reflectometry techniques (Time Domain, Sequence Time Domain, Spread Spectrum-Time Domain and a new Spread Spectrum Frequency Shift Time Domain Technique) was developed and verified experimentally for Time Domain Reflectometry in coaxial cables and CAN twisted pair wires. Since in a fault condition an impedance variation occurs which causes different reflections of the voltage wave, it is possible to determine the fault condition and its spatial location in a cable. Different cross-correlation and wavelet analysis digital signal processing techniques were tried out.

Thesis Supervisor: Pablo García Fernández
Title: Associate Professor

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Chapter 1

Introduction

Since the time when the first cars were electrified with auxiliaries, wires were treated as a system that, once installed, worked for the whole lifetime of the vehicle. Nowadays however, because the expected lifespan of auto-mobiles has increased and because the electricity distribution systems and communication buses they're equipped with have become much complexer, the probability of occurring faults has also raised.

Driving key factors in automotive cabling are the cost, the assembly easiness and the quality. The aggressive environment most of the cables are in, is accelerating the ageing of the wiring. This is a problem that has not been treated seriously so far and wires were empirically dimensioned. In recent years the cars have started to be even more electrified. The on-board equipment has become more complex, cars are being equipped with more and more electronic control units (ECUs) and drive-by-wire systems might be a normality in the nearby future. All this leads to a drastic increase of the weight, length and volume of the cabling. This added weight results in an increased fuel consumption. That's why today, a lot of effort is being made into optimizing the existing bus systems and reduce the cost and weight of the wiring. This will lead to optimally sized conductors and insulators and the problem of ageing, soft and intermittent faults should be more seriously considered as oversized wires will be less and less common; thinner wires are more likely to fail because of mechanical stress.

Electric and hybrid electric vehicles are also becoming increasingly common. The criticality of the wiring is even more important in these cases. Because the new full-electric vehicles, controlled fully by ECUs, will become more and more present on the market, the reliability of the wiring network and the safety are becoming crucial, as the mechanical coupling that creates control redundancy might be eliminated in whole.

Conventionally, network problems are being detected and isolated with network management. All nodes of the network periodically transmit a message that shows that the specific ECU is on-line and working. In the case that a node is missing, a fault routine, that might be a reset or an emergency shut down, is usually run. [29]

Maintenance is hard and time consuming, because of the integration and packaging of the cables in the restricted spaces in the chassis. According to [30], in some cases, repairing a cable defect in the wire harness can take up to two days for a skilled mechanic. During the troubleshooting process more ECUs might be changed out of which according to some automotive Original Equipment Manufacturing (OEM) companies only around 30% are indeed defective.

This is why a new fault detection technique for the cables that could also give a localization within a decent margin of error is desired. Even though, from a safety point of view, the traditional network management based method gives good results, a lower layer level technique will have many unique advantages. Through the use of smart wire health monitoring in the physical layer of the on-board electrical system of cars, intermittent faults created by soft faults (degradation in insulation) could be promptly detected before they create continuous hard faults (short circuits, broken wires) that could endanger the overall safety of the vehicle.

The same technology could lead to the development of a device for confirming the correct installation of cables in vehicles and even verify that they are according to a standard, thus increasing the quality. Then, with slight modifications it could be used in the repair shop for finding and locating electrical faults. The method could potentially improve the reliability of cables and should be implemented in safety related critical systems (ABS, ESP, air-bags, servo-steering, etc.). Such a technique could also be applied in detecting the faults in electric motors and power converters. [27]

A technology that has proved itself in the domain of fault detection and location is reflectometry. It has been originally used for locating faults in power and transmission lines and lately has moved to the domain of transportation for detecting faults in ageing wiring in the aeronautical industry.

Reflectometry has the big advantage of only using one end of a cable for testing the wiring and could be employed in the automotive sector too. It could have a significant impact on the overall health monitoring of the system. These techniques are beautiful through their simplicity and work similar to the radar. A stimulus signal is inserted into a conductor and the impedance changes in the wire create different reflection times at the connection point. These are measured and can be interpreted through different digital signal processing algorithms as connectors, loads or faults. The reflectometry encompasses many different techniques that differentiate themselves through the input stimulus signal that they use. Among these, Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), Joint Time Frequency Reflectometry (TFDR), Sequence Time Domain Reflectometry (STDR) and Spread Spectrum Time Domain Reflectometry (SSTDR) are the most commonly found in the specialized literature.

For all the above mentioned reasons, this thesis investigates the topic of fault detection and location for automotive cables. It offers a review and study of feasibility of some fault detection techniques, whilst concentrating experimentally on the Time Domain Reflectometry. It gives a theoretical background review and investigates the possible applications of such techniques to vehicles.

A new Spread Spectrum Time Domain Reflectometry Technique with Frequency Shift Keying is tested in simulation and the model is partly validated experimentally.

Different measurements with Time Domain Reflectometry are made on an experimental set-up for CAN twisted-pair 120Ω and coaxial 50Ω line impedance cables. Usual hard faults are tried out for wires of different lengths while two different stimulus signals are used.

A Digital Signal Processing(DSP) algorithm for the automatic edge detection of the reflections, based on the continuous wavelet transform with *haar* wavelets is developed and tested experimentally and through simulations for CAN twisted-pair open ended wires.

Different sampling rates are used for measuring reflections in a CAN twisted pair cable in order to try to determine the minimum hardware requirements for such a fault location algorithm in a system with a limited rise time. This excitation signal is compared with the CAN signals measured in a vehicle to assess the feasibility of implementing a CAN signal based reflectometry technique for the CAN bus.

An experiment is made in order to prove that reflectometry could be eventually used to check the correct installation of grounding cables in vehicles. This is desirable because sometimes the connection point of the grounding cable in vehicles is faulty by cause of a thin layer of non-conductive paint that covers it and therefore more susceptible to failures.

This work was mostly developed during an internship[1] as part of the fourth semester of the EMMC STEPS program. In the next chapter the activities developed during this internship, aside for the one related to this thesis, are presented. In the chapters that follow it, the motivation and challenges are analysed, and then, the objectives of the thesis are stated. The state of the art of fault location techniques and of reflectometry is reviewed. The challenges are considered and evaluated and potentially low-cost solutions for fault detection and location are proposed in simulation and partly validated experimentally.

The master thesis is meant to give an overview of the state of the art on fault detection and location in wiring and a general framework of this topic with an application to the automotive cabling.

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[1] The internship was fulfilled in the Cable Department of the Technical Centre at SEAT Martorell S.A.

Chapter 2

Internship Activities

The Internship, part of the fourth semester of the EMMC STEPS program was spent at SEAT Martorell S.A. in the cable and packaging department of the technical centre.

The activities done there were split into two parts: one was working on an automatic method of pairing fuses and cables for weight optimization of the cable harness in vehicles and the second one was a fault detection and location project, applied to automotive, the subject of this Master thesis.

In the automotive industry, cables are and have been mostly sized empirically, so the introduction of a new optimization software tool is highly desirable. This tool would achieve the weight optimization of the wire bundle in two consecutive steps. At first, the optimum fuse would have to be chosen in accordance to the steady-state and transient currents on the loads. The second step would consist in selecting the appropriate wire for the fuse, that should be properly protect even in the worst thermal conditions.

The scope of the project is the noticeable reduction of the weight of the copper in the cable harness of a vehicle. For that, a reliable worst-case heating curve of a cable has to be generated and then the optimum cross section of the cable could automatically be chosen by identifying these curves with the tripping curves of fuses. These tripping curves are given by the manufacturer of fuses in datasheets.

For the project, of weight optimization of the cable bundle, more unrelated tasks had to be fulfilled:

At first data had to be gathered from many fuses datasheets (Littelfuse) and centralized into an excel spreadsheet. The most important data were the Time-Current Characteristic Curves and the Temperature Rerating Curve, data that concern the desired tripping curves. These gathered critical points were then plotted with Matlab and a function able to interpolate other values on the curves was created in order to reconstruct the original curve. More interpolation methods were used to obtain the best matching curves and the minimum and maximum arcing times for a given temperature and different current values were returned by the function.

Another task was gathering information about the thermal conductivity, the specific heat capacity and the density at different temperatures for the insulation materials (PE, PP, TPE, PVC, etc.) and conductive ones (Al, Cu) used in automotive cabling. This information was than centralised in spreadsheets in respect with the temperature. The information were to be used in a finite element algorithm for the optimization process.

One of the last tasks was to create a Matlab function that could read an ID of a cable given in the group standard VW60306 (correspondent group standard of the DIN 76722) and give information about the part. These information refer to the type of cable, conductor material, geometric construction of insulation, insulation material, constructional elements, conductor cross-section and construction, surface conductor coating, etc.

The second part of the Internship was developing a fault detection technique that could be applied for the DC bus and communication buses of a vehicle, scope of this thesis. The weeks were split into two parts. One where the above mentioned tasks were fulfilled and the second one where the work for the thesis was made.

Chapter 3

Motivation and Challenges

According to [30], in 1950, the electrical system of a small car like the Peugeot 203, comprised of only 50 wires. The cars nowadays have more than 1000 wires, due to the increasing number of ECUs that need to be interconnected. All control units and wiring in a modern car fulfil high quality standards, but even so, faults may occur due to the harsh environment certain areas of the cable harness are exposed to. The high differences of temperature (most cables and fuses are designed for temperatures ranging from -40°C to +105°C or +125°C), water infiltration (water with salt during the winter when used for melting the snow), a lot of vibrations and other mechanical stress factors (moving components) contribute to this harsh environment.

That is why even with the highest quality standards, plugs may corrode, water might infiltrate in connectors, the isolation of the wires might be damaged, cables may break, tranceiver ICs may be damaged by electromagnetic interferences, etc. [29] The desire of detecting soft faults, i.e. defects in the insulation, is easily understandable as these are at the origin of the intermittent faults that can further on create real damage if they become continuous hard faults.

Because more and more power is needed for the loads on the DC bus of a vehicle, many car manufacturers want to introduce a new standard for the voltage level of the DC bus (that is 48V instead of 12V that is currently commonly used). The probability of initiating series or parallel arc faults is increasing because of this tendency and also due to the fact that in hybrid and electric vehicles where the DC voltage of the power

Figure 3-1: Wire Harness [2]

source can reach more than 300V are becoming more common day by day. According to [30], the duration of an arc fault is typically shorter than 1 ms. Therefore, the detection of such faults could only be implemented on-line.

The complexity of a typical wire harness can be appreciated in figure 3-1. The number of wires is bound to grow as more an more ECUs are added and integrated in the buses of the vehicles.

Reflectometry techniques have proven themselves in many domains for fault detection and location in wiring and could be therefore used as an on-line embedded diagnosis systems in order to detect such faults with a short duration and also other more typical hard-faults.

The biggest challenge of applying reflectometry to automotive cables is the fact that such wires are very short in comparison with other ones for which these techniques have already been implemented, i.e. power and transmission lines, aeroplane communication and power wiring, ships cabling, space shuttle, etc. For example, on the new model of a SEAT Ibiza, the shortest wires are a bit longer than 10 cm and the longest are a little shy of 6.5 meters. The wiring in such domains is at least to a tenfold longer than on a small car like the Ibiza. That means that a reflectometry system would need to be ten times faster than the best ones in the other domains.

Considering that when using reflectometry one deals with wave propagation speeds of around two thirds of the speed of light (for example 200000 km/s for CAN twisted pair 120Ω impedance wires), very high sampling rates are required for the constant monitoring of the wire. In such a cable that is 1 meter long, a wave travels forward and backwards in 10ns. In Time Domain Reflectometry (TDR), the accuracy is given by the rise time of the pulse/step and the sampling rate of the receiver. In the case of a pulse, the narrower the width of the incident wave, the smaller the energy it transmits and a higher bandwidth of the sampler is needed in order to distinguish between the incident and the reflected pulses. [34]

Therefore, when using TDR to locate the fault, very high sampling ADCs (Analogue Digital Converters) are used, which can lead to expensive devices. Even so, the sampling rate could be decreased, as in automotive cables, the bus topology is known and locating the fault to an exact position is not as important as locating it into a segment of the cable harness.

Portability is another challenge that has to be addressed. A car manufacturer usually fabricates more models that have different cable harnesses. Also within the same model, no two cable harnesses are the same, because these are hand assembled and the involved human factor leads to some margins of error that have to be addressed by the fault detection and location method. When using reflectometry, this could be overcome with a simple empirical algorithm that monitors the change of a reflectogram of a wire/bus in regards to a reference profile. When this change is not high, no fault will be denoted. Yet when a considerable difference occurs, the fault condition is identified and its location estimated. Through the use of such an algorithm and the application of fuzzy logic methods, distinguishing between faults and connectors is also possible. This reference profile could be dynamic, static or even based on simulations. [29]

Soft faults create very small impedance changes and are therefore very hard identifiable with reflectometry which needs consistent variations for reading the reflections easily. In [21] it is explained why these frays were not detectable with the state of the art reflectometry techniques that were used at that moment (FDR, TDR, STDR and SSTDR). It is shown that the peak values for the TDR output for different frays, chafes, removed insulation and water on removed insulation are smaller than the peak values of the movement noise and hardware noise. Therefore identifying these types of soft faults with TDR is virtually impossible, even with the best available instruments.

However, newer Joint Time-Frequency Domain Reflectometry techniques are trying to address this challenge. In [20] and [38] through the use of TFDR, incipient defects were located with high accuracy for two different types of coaxial cables used on ships and aeroplanes. These promising results with this technique are till now limited to coaxial cables and additional work must be done to explore the application of TFDR for cables other than of coaxial type.

In [28] another new TFDR technique is suggested for detecting the soft faults in wire bundles. This method is called Cluster Time-Frequency Domain Reflectometry and introduces the new idea of using the near end crosstalk signals through a clustering process in order to maximize the posibility of detecting the small impedance changes that correspond to soft faults. This method was tested experimentally, but as the other TFDR ones, still needs more work and further development for a real world application.

Some other approach for soft fault location uses the concept of Matched-Pulse (MP) Reflectometry. [22]. The idea of the MP technique is to use the properties of time-reversal signal processing. Thus the return echo from a cable could be maximized while using the same amount of excitation energy. The advantage of this method in regards with TDR was experimentally demonstrated for complex wire systems. The same authors make a similar study in [23]. Again, this technique is not mature enough and no industrial solution is yet available.

As previously mentioned, reflectometry has the big advantage of only needing one access point of a wire in order to evaluate it. The methods used for fault location are implemented on individual conductors at a time. In the automotive sector more cables are interesting for the implementation of a fault detection and location system. A multiplexing method would therefore have to be developed and employed for the continuous monitoring of the cabling.

Chapter 4

Objectives

The main goal of this Master thesis is the theoretical and experimental study of fault detection and location methods for the DC and communication buses for the automotive sector. This work is meant to highlight the need of such methods in the industry and offer a kick-start for further work on fault detection for cabling in vehicles and short wiring in general. It also encourages future studies in this domain. Among the objectives of the thesis one could mention:

1. Review of the state of the art of the fault detection techniques: because the state of the art of currently applied reflectometry methods to the cables of cars is limited, a study of the most appropriate reflectometry techniques is made; the applicability of different methods for this new domain is investigated.

2. Develop a simulation model for reflectometry: more models were developed for TDR, SSTDR and a new model for SSTDR with frequency shift keying instead of phase shift keying was built. This technique could present some advantages in comparison with the regular SSTDR due to the fact that the signal processing could be potentially effectuated easier.

3. Validate the simulation model experimentally: the model for TDR was validated experimentally for controlled impedance cables. Two types of cables (coaxial and twisted pair) and two input signals (pulse and step with slow rise time) were used to confirm the validity of the model.

4. Make different measurements: experiments with different signals, different sampling rates, different wire lengths, fault types and loads were made. The voltage was primarily evaluated, but the current was also examined through measuring the voltage drop on a resistor with a known value. The experimental results were again checked with the simulation model.

5. Develop the Digital Signal Processing for the localization of the fault: two different algorithms were implemented; one for the simulation model of SSTDR and SSTDR-FSK that uses the cross-correlation to distinguish the impedance mismatches of a cable and another for the TDR waveforms obtained experimentally and confirmed through simulation for the automatic edge detection with the help of the wavelet analysis.

6. Investigate theoretically possible uses of reflectometry for the automotive sector with minimal cost: fault detection and location in the DC bus, fault detection and location in the communication buses, verify the correct installation of cables, verify that the cables are according to a standard, detect the faults in their incipient moments before they create real damage, investigate the possible use of existent signals for inserting as stimulus in the cabling and search into the passive monitoring of the physical layer of the communication buses.

Chapter 5

State of the Art

5.1 Fault Location Techniques

To understand which fault detection techniques could be implemented for the automotive industry, for the DC and communication buses, one must first consider the techniques used for detection and location in cabling in general. According to [26], the fault location methods for distribution power systems can be divided into the following categories:

1. Impedance and Other Fundamental Frequency Component Based Methods.
2. High Frequency Components and Travelling Wave based Methods.
3. Knowledge Based Method.
    (a) Artificial Intelligence and Statistical Analysis Based Methods
    (b) Distributed Device Based Methods
    (c) Hybrid Methods

However, most of these methods are only appropriate for larger scale power systems than the ones of a vehicle. In [30] a review of the wire troubleshooting and diagnostics techniques is made and a short comparison of diagnostics methods is offered, as follows in Table 5.1.

Table 5.1: Comparison of diagnosis methods [30]

Method	**Advantages**	**Disadvantages**
Visual Inspection	Provides location information	Strongly depends on the operator, requires full access to the cables
X Rays	Can detect any kind of defect, provides location information	Requires heavy systems, inappropriate for use in transport systems
Ultrasound Guided Wave	Can detect insulator defects, i.e. soft faults	Needs complete access to the cable and is not suited for branched wires
Infra-red Thermal Imaging	Provides location information	Requires complex imaging system, and can only detect faults that create a hot spot
Continuity Measurement	Provides quick continuity information	Requires two access points to the cable, does not give information about the location
High Pot	Can detect insulator defects	Require heavy systems and might create additional damage to the cable under test
Reflectometry	Only needs one acces point and provides location information. Suitable for complex topology networks.	Hard to discover soft faults, sometimes complex DSP algorithms are required, challenging to use in short wires. The topology of the network needs to be known in order to locate faults in branched networks. Can be expensive.

Capacitance and Inductive Sensors can also be used to measure the distance to a hard fault and offer a lower cost alternative in comparison with the reflectometry techniques. These have the disadvantage that they cannot be used on live wires, nor do they give good results in branched ones. [39] For these reasons this types of sensors are not that interesting for being employed in the cable harness for on line fault detection. Some application could be found for individual wires.

5.2 Reflectometry Techniques

Due to its advantages and potentially overcomeable disadvantages, the reflectometry techniques can be considered to give the best implementation for fault detection and location for the automotive sector. Reflectometry is a non invasive method of obtaining the properties of the analysed medium out of the reflections of a stimulus inserted wave. The data that results out of reflectometry at the connection point is depicted on a reflectogram. This data offers numerous information about the device/network under test when adequate digital signal processing is applied.

The scope of this study being the detection of faults in cabling, means that the devices under test will be in this case the individual wires that form the DC network and communication buses in a vehicle. Nonetheless, when applied to the automotive domain, reflectometry isn't just limited to cabling and could be used for detecting faults in electric motors or power converters. The reflectometry techniques vary through the signal that is chosen as stimulus and the corresponding digital signal processing algorithm that is able to detect the impedance changes and obtain the location of those.

Reflectometry Techniques are split into two main categories: Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR), but hybrid methods such as Joint Time-Frequency Domain Reflectometry also exist and are under development.

5.2.1 Time Domain Reflectomtry (TDR)

TDR is the easiest understood reflectometry technique. In TDR more input signals such as sharp pulses (gaussian, mexican hat, square, etc.) or voltage steps with a small rise time are used as stimulus. These waveforms reflect a part of their energy back to the connection point when impedance mismatches occur. For simple networks, the reflected waves are also steps and the distance up to a change of impedance can be calculated from the time delay between the incident and reflected waves, once the propagation speed is known.

TDR methods are very appropriated for complex topology networks where each peak/step will correspond to a discontinuity in the network. This can be a connector, a bifurcation or a hard fault. Due to it's high bandwidth, if an initial extremely accurate baseline is available, soft faults could also be, in theory, identified. One problem that the TDR devices have is the one of the "blind spot". This refers to the detection of discontinuities in the first part of the wire where the device is attached. Due to the very high speed of the wave and the width of the incident wave, sometimes the reflected voltage overlaps the incident one and in the case of sharp pulses it is very hard to distinguish the two one from the other. One way of counteracting this problem is through adding an extra length of cable to the testing one.

TDR is not optimal for live wire testing due to the fact that the reflections are hidden under the noise margin of the signals in the wires that are being tested. [32] Withal, in the case of a DC bus, TDR can be easily implemented on-line as the sharp pulses wouldn't interfere with any signals. Moreover, the case of the blind spot could be also addressed with the use of a hybrid step-pulse method similar to the one used in [7] for the automatic interpretation of reflectometry traces. Here, through the use of the continuous wavelet transform, it was shown that with such an algorithm both reflectograms with mixed echoes (blind spot) and with non-mixed echoes could be identified. A similar algorithm, to a 10 times faster scale, was experimentally verified and is presented in subsection 7.1.2.

The paper "Reflectometry based Fault Localization in Automotive Bus Systems"

[29] describes one of the few direct applications of TDR to the car industry. Here, in order to detect the faults and localise them, the authors apply a stimulus to an existent bus. This must not disturb the operation of the bus and should ideally be a *sinc* sloped pulse with limited bandwidth, which in the end will be a trade-off between rise time and electro magnetic interference. After this first step, the device will learn the correct echo (reflected response) to the given stimulus of a network without any faults and then will proceed to evaluate the echo over and over again. First the echo is preprocessed. The DC level of the reference echo and measured echo are matched (through averaging of several samples before sending the stimulus waveform) and the precise time where the input wave is maximum is assessed. Then the calculation of the difference occurs after taking into account the damping effect and compounding (i.e. the ADC is not linear for a better resolution). Now it comes to localizing the problem when there is a difference between the reference and measured profiles. The faults should correspond to the peaks, but there are more peaks caused by noise and multiple reflections, so a cross-correlation of the echo and stimulus signals is done, thus removing many irrelevant peaks. Then fuzzy logic was applied, attributing a score factor for every signal, with a higher factor for the preferred signals, thus getting a temporal location of the potential problem. In order to visualise the problem, a netlist of the network that assigns every component a probability of failure is needed. Short cables, long cables, junctions, plugs and sockets have an increasing probability of failure. Thus the network component with the highest probability is identified when only an ambiguous distance from the measurement point is given at the beginning.

Sequence Time Domain Reflectomtry (STDR)

In order to increase the energy of the pulse and make TDR more immune to noise, the input signal is spread over the spectrum in baseband. This is done through the use of a PN (Pseudo random Noise) Sequence as a test signal. Thus Sequence TDR, or STDR takes form. Figure 5-1 shows the schematic for STDR and for SSTDR. In the case of STDR, the BPSK (Binary Phase Shift Keying) modulation shown in the figure is not effectuated.

In [31] and [11] an analysis of STDR is made with a direct application for aviation cables and in [19] the use for transmission lines, especially telephone ones, is investigated through simulations and experiments.

More on this technique is offered in section 6.2.2.

Spread Spectrum Time Domain Reflectomtry (SSTDR)

The difference between STDR and SSTDR is that by SSTDR the output of the PN Sequence generator is multiplied with a sine wave, thus obtaining a Direct-Sequence Spread Spectrum (DSSS) Binary Phase Shift Keyed (BPSK) input signal as seen in figure 5-1. After this additional step the signal processing is done according to the figure as in the case of STDR. A more thorough explanation of this technique is given in section 6.2.2.

The papers [19] and [31] address not only STDR but also SSTDR. More about SSTDR applied to the cables in an aeroplane can be found in [40]. In this case a theoretical and experimental study is made for detecting and locating the faults on the 115V/400Hz cables that are commonly used in the aeronautical industry.

As mentioned earlier, due to the increasing voltage in the DC bus of a vehicle, the arc fault detection has become of critical importance. A feasibility study for location of arcs on live wires through SSTDR for the aeronautics sector is given in [16]. The offered results shown in the paper seem promising.

A modified SSTDR method of detecting on line faults is presented in [6]. Through a spectral modification of the injected signal, the stimulus is adapted to the application constraints. The advantage of this modification is the fact that it avoids the low frequency perturbations.

SSTDR has many other uses aside from diagnosing cabling. One of the most interesting is presented in [27], where the state of health of power converters is estimated through the use of the technique.

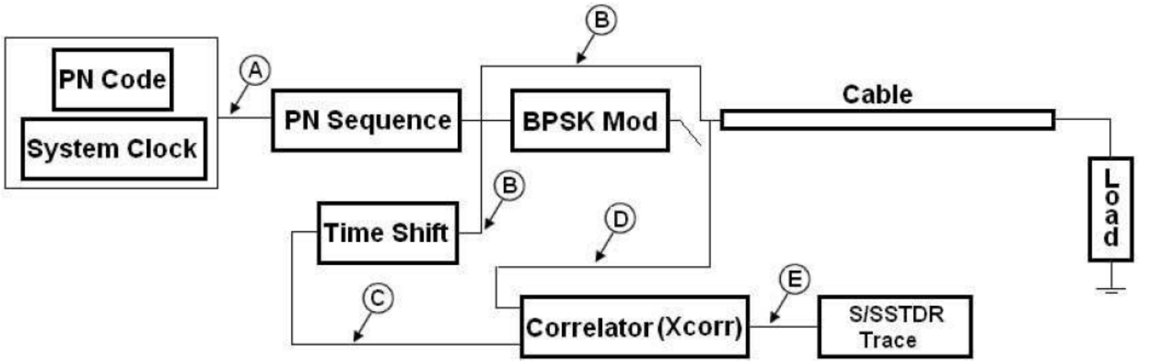

Figure 5-1: S/STDR Schematic [19]

Multi Carrier Time Domain Reflectomtry (MCTDR)

In Multicarrier Reflectometry, the generated signal is obtained by an Inverse Digital Fourier Transform (IDFT). The input can therefore be fitted to the constraints of the application as the spectrum of the test signal can be arbitrary. This technique is important in applications where very strict EMC constraints are present. The method needs reliable post-processing in order to obtain usable results due to information loss. [8] [30]

Orthogonal Multi-Tone Time Domain Reflectomtry (OMTDR)

OMTDR is based on Orthogonal Frequency Division Multiplexing (OFDM) [30] and divides the bandwidth into multiple sub-bands through the use of closely spaced orthogonal tones. [35]

In [37] the technique is verified through simulation in a coaxial lossy cable, in [36] for a branched network and in [35] for a CAN bus.

5.2.2 Frequency domain Refectometry (FDR)

FDR utilises a set of sinusoidal signals with a fixed frequency bandwidth and analyses the changes in frequency domain. Three different parameters are monitored in the variations of the technique: frequency, magnitude and phase. FDR was easier and cheaper to implement in the past, but the decreasing price of electronic components made TDR be more competitive. FDR isn't that well suited for complex network topologies because of the difficulty of analysing the multiple reflections and interactions of the wave. Therefore FDR isn't a prime candidate for implementation in the automotive cabling, that consists out of networks that can be complex. [30] [32]

Frequency Modulated Carrier Wave (FMCW)

FCMW works through measuring the frequency shift between an incident and reflected signal. The incident wave is generally a sine wave that varies very quickly according to a ramp function and the time delay can be calculated when the speed at which the frequency is stepped is known. This technique hasn't been implemented to wire applications due to the very high speed constraints. [32]

Phase Detection Frequency Domain Reflectometry (PDFDR)

The hardware for a PDFDR device consists out of a VCO (Voltage Controlled Oscillator), two directional couplers, a mixer and its control circuitry. All these could be integrated onto a single chip and automatic analysis could be made even for branched wires. The technique is not optimal for implementation on live wires and special algorithms need to be developed to eliminate the low frequency when testing cables of a length that is shorter than 1 meter. [32]

PDFDR basically works through measuring the phase shift between incident and reflected waves. The VCO supplies a sinusoidal over a given bandwidth with a frequency step size. The incident wave travels as usual through the test cable and is reflected back, but the reflected signal is isolated through a directional coupler. It is then sent to a mixer where it is multiplied with the incident one, resulting in signals at the sum and difference of their two frequencies. The mixer outputs a DC voltage which is proportional to the length and load of the line. The number of periods of the DC voltages depends on the length of the line. A FFT (Fast Fourier Transform) of this signal will give single spikes at the end of the line so that its length can be calculated. [32]

Standing Wave Ratio(SWR)

Standing Wave Ratio monitors the magnitude of the wave created through the interference of the incident wave with the reflected one. Peaks and nulls will therefore be present in this standing wave and two different methods of analysing the network are available:

Null Detection. Here, the frequency is stepped till a null in the standing wave is found, a null which corresponds to an impedance change. The accuracy of the SWR null detection is comparable to the one of the PDFDR, but this technique has difficulties in discovering small impedance changes and thus limits it to the detection of hard faults. Due to the complexity of detecting the nulls when multiple reflections occur in branched wires, this SWR method is confined to use for simple configurations. [32]

Magnitude Detection. This method challenges the limitations of the null detection technique through measuring the wave at every frequency therefore being able to extract the information of the multiple reflections. MSR (Mixed Signal Reflectometry) is similar to the PDFDR but doesn't need the directional couplers, hence making it cheaper to implement. However its limitations are similar to the ones of PDFDR. MSR is more accurate than the null detection SWR, but is still not capable of detecting soft faults such as frays or chafes. [32]

5.2.3 Joint / Time Frequency Domain Reflectometry (J/TFDR)

A new promising technique is the (Joint) Time Frequency Domain Reflectometry. Unlike traditional TDR and FDR, TFDR uses a chirp signal with a Gaussian envelope as stimulus and through the calculation of a time-frequency cross-correlation function it manages to amplify the very small impedance changes up to the level of hard faults. The Gaussian envelope of the signal localizes the inserted signal in time and frequency

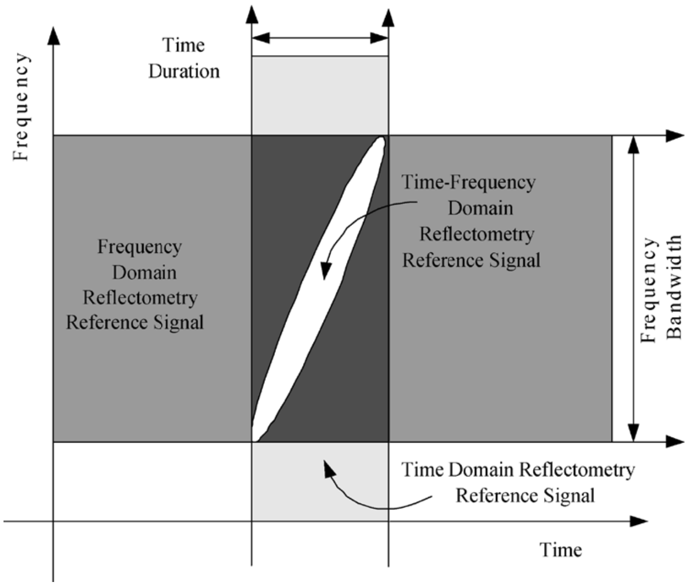

Figure 5-2: Reference signal comparison for TDR, FDR and TFDR [38]

and the instantaneous frequency of the signal increases linearly with time. The biggest advantage TFDR offers in comparison with the rest of the reflectometry techniques is the potential of detecting the faults before they can cause real damage. [30] [38] [34]

In order to be accurate the reference signal must be designed so that it matches the physical characteristics of the wire under test. First, the center frequency has to be determined. This gives the degree of attenuation of the reference signal in the cable. A trade-off between spacial resolution and attenuation is made. Then the frequency bandwidth is selected, this being usually limited to the performance of the signal generator. The time duration is also limited by the same factor. [38] In 5-2 a comparison of the reference signal to traditional TDR and FDR can be observed.

For the detection of the impedance discontinuities, the cross-correlation between the reference and the reflected signal is effectuated. A block diagram of a TFDR system for locating faults on a cable can be viewed in figure 5-3.

In [38] TFDR is introduced and compared to classical TDR and FDR for locationg the faults in a coaxial cable. There are other papers that address this same topic. In [20] more testing for coaxial cables is done for the diagnostics and prognostics of

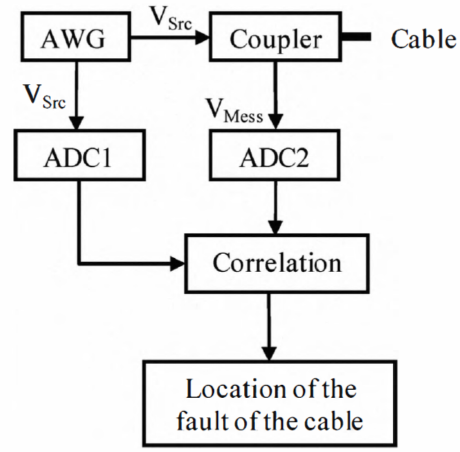

Figure 5-3: Block Diagram of a TFDR System [34]

electric cables in ship power systems. Another similar work is done in [18]. [17] verifies TFDR for multiple wiring faults while taking into account the multiple reflections. Another study that compares this technique to TDR and FDR is [34].

Although TFDR appears to be the solution for detecting soft faults, none of the above mentioned papers address the problem of field implementation. Due to the high computational burden of the TFDR's cross-correlation function, no field uses have been made so far. However, [12] proposes a new technique to reduce the computational time through deriving "the second order time varying AR model of Gaussian enveloped linear chirp signal and estimate the instantaneous frequency (IF) by using the weighted robust least squares (WRLS) estimator." [12] Out of the instantaneous frequency, the location of the faults can be estimated. This procedure has been verified through simulation only, but the paper gives a good direction for future field implementation of the promising TFDR systems. Other methods rely on the Hilbert Huang Transform, an empirical modal decomposition method to try to reduce the computational time. [30]

Even with quite a few studies on TFDR on the problem of soft fault detection and the indication that this might be solvable in the nearby future, there is still a lot of work to be done before an industrial application of this method is implemented.

Due to the immaturity of the technique, it is not a suitable candidate, for now, for the fault detection in the cabling of a vehicle, but could become soon in the following years.

5.2.4 Time Reversal Reflectometry (TRR)

[25] introduces for the first time the concept of a matched pulse approach for fault detection and shows the benefits of this technique through mathematical modelling and simulations. This technique is based on Time Reversal techniques.

Unlike the other reflectometry techniques, where a predefined signal is inserted into the NUT (Network Under Test), in the MP approach a tailored stimulus is inserted so that the energy of the reflection of the fault is maximized. A matched filter is obtained by correlating a known template signal, with an unknown signal in order to detect the presence of the template in the unknown signal. "This is equivalent to convolving the unknown signal with a time-reversed version of the template. The matched filter is the optimal linear filter for maximizing the signal to noise ratio (SNR) in the presence of additive white noise." [25]

The same authors did further investigations on this matter in [24], [22] and [23] where they have also tested the method experimentally for the detection of soft faults. It was shown that TRR actually gives more accurate results in networks that are more complex. This makes it interesting for a possible implementation in a automotive bus system.

5.2.5 Noise Domain Reflectometry (NDR)

One last interesting reflectometry technique is the Noise Domain Reflectometry proposed in [10]. Based on the properties of autocorrelation which measures how similar or different two signals are, NDR can be used to determine the time delays in simple or branched wires.

The main advantage of NDR is that it can operate completely silent in networks where additional signals can not be over-modulated or added. NDR uses the existing signals or noise in the NUT as the test signal. These waveform are used exactly as in regular reflectometry, as they create reflections where impedance discontinuities are present. Since a sliding window of a few milliseconds is used for the test signals, one could say that this is completely random. Through the correlation of the test signal and the reflections, peaks appear, indicating the location of the impedance changes.

There are two types of NDR. One in which separate copies of the test signal and the reflections are needed (achievable through a directional coupler) and another one which analyses the superposition of the test signal and its reflections, which has the advantage of being more cost-effective since the coupler can be expensive.

NDR has the same limitations as most of the other reflectometry techniques for detecting soft faults, but could be interesting for the use in the automotive industry for the communication buses where the integrity of the signals is important. A dynamic baseline could be obtained and variations from this baseline could lead to the discovery of intermittent faults.

5.3 Devices

There are many available hand-held devices on the market for detecting faults in cabling. However they are mostly designed for the detection on long transmission lines or power cables of thousands of meters, and aren't optimized for the short distances the cables in cars have. Most of them work with TDR narrow pulses and offer an unsatisfactory resolution of about half a meter. Some devices give a distance up to a possible fault, while others have a small display on which the waveforms of the reflections can be seen. The user needs in this cases to be skilled enough to read the reflectogram in order to identify a fault location. Other similar devices use SSTDR instead of TDR and have the advantage of being able to detect the faults in on-line cables.

LiveWire Innovation has developed an Application Specific Integrated Circuit (ASIC) that uses Spread Spectrum Time Domain Reflectometry (SSTDR) to detect and locate faults on up to four different individual wires. [3] [33]The LiveWire

ASIC can be integrated in many domains thus reducing maintenance, troubleshooting or monitoring costs and increase the system reliability. LiveWire's ASIC is able to monitor changes in wiring systems, in real time. "Changes that occur for as brief a time period as one millisecond can be detected, characterized, and located (distance to fault) within an accuracy of +/- 2% over distances from a few inches to hundreds of meters." Among the key features of the ASIC one can mention: Spread Spectrum Time Domain Reflectometry as core technology, continuous monitoring on 1 channel with around 3000 scans/sec or multiplexed monitoring on 4 channels with between approx. 2000 scans/sec and 500 scans/sec on each wire, arc fault capture mode, able to monitor cables up to more than 1500m long. [3]

Another interesting product is the Fluke Scopemeter 120 Series which is a handheld oscilloscope. With higher than 1GS/s these devices allow the user to see the signals on the communication buses and could be used to debug the physical layer of a CAN bus. The peak-to-peak voltage and rise time can be measured with this instrument and it allows the signal details to be examined. [13]

Chapter 6

Theoretical Background

In this chapter the most important principles, models and digital signal processing (DSP) techniques that are used in chapter 7 are summarised. The cable modelling for reflectometry, SSTDR, wavelet theory and the problem of detecting soft faults are approached and briefly explained.

6.1 Cable Modelling

In reflectometry, the signal that propagates along the cable changes faster than the time it takes the wave to propagate along the wire. Therefore the cable can be treated as a transmission line. [29]

According to the transmission line theory, an infinitesimal piece of a cable is modelled as presented in figure 6-1. This model is characterised by the telegrapher's equations. E_S represents the voltage of the signal generator, Z_S is the inner impedance of the signal generator and Z_L the load impedance. The frequency dependent parameters L, R, C and G are the series inductance in H/m, the series resistance in Ω/m, the shunt capacitance in F/m and the shunt conductance in S/m.

Considering the line infinitely long and L, R, C and G defined per unit length,

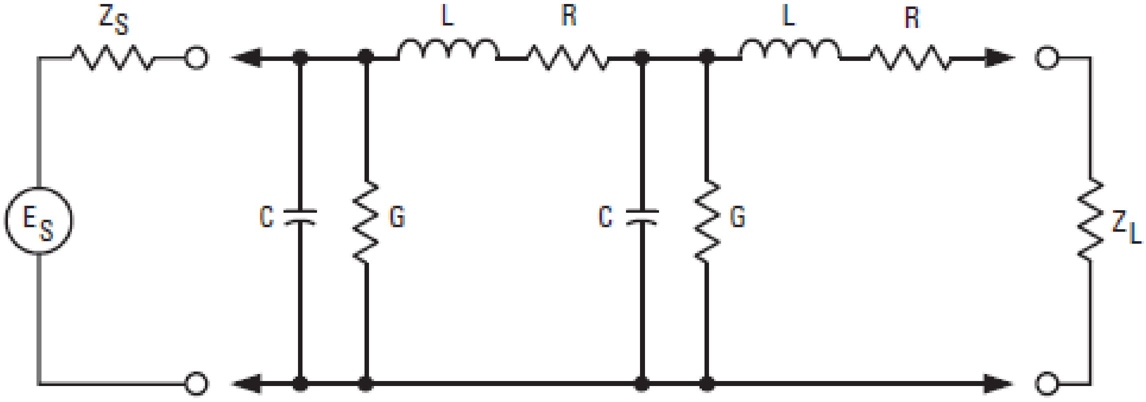

Figure 6-1: The classical model for a transmission line [5]

then the input impedance can be given as [5]:

$$Z_{in} = Z_O \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{6.1}$$

Here, Z_O represents here the characteristic impedance of the line. A voltage step/pulse requires a finite time to reach a point down the transmission line. The phase of the voltage moving down the line lags the inserted voltage at the end of the line with β and is attenuated with α, where γ, the propagation constant is given as:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{6.2}$$

The propagation velocity v of the voltage line can be approximated as it is given below, and when losses and frequency dependent variations in the dielectric are ignored:

$$v = \frac{\omega}{\beta} \simeq \frac{1}{LC} = \frac{c}{\sqrt{\epsilon_r}} \tag{6.3}$$

The current and voltage at a given distance x can be calculated with the help of the propagation constant:

$$E_x = E_{in} e^{-\gamma x} \tag{6.4}$$

$$I_x = I_{in} e^{-\gamma x} \tag{6.5}$$

And the characteristic impedance of the line will be:

$$Z_O = \frac{E_{in} e^{-\gamma x}}{I_{in} e^{-\gamma x}} = \frac{E_{in}}{I_{in}} = Z_{in} \tag{6.6}$$

When the transmission line is of a finite length and the load is different from Z_O the above equations are only satisfied if there is a second wave that propagates from the load back to the source. This energy is therefore not delivered to the load and the quality of the transmission line will be indicated by a voltage reflection coefficient ρ [5]:

$$\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_O}{Z_L + Z_O} \tag{6.7}$$

6.2 Injection Techniques

6.2.1 TDR

Figure 6-2 shows how a display for a TDR measurement looks like in terms of the load and reflection coefficient ρ.

The shape of the reflected wave can give valuable information. With the help of equation 6.7, by measuring E_i and E_r one could get Z_L in terms of Z_O or vice-versa. [5]

This is valid for most communication cables used in the automotive industry. Figure 6-3 shows the reflectograms for some complex load impedances. To analyse the waveforms, the reflected voltage at t = 0 and at t = inf is evaluated and any transition between these two values is assumed to be exponential.

In TDR, a stimulus signal is inserted into a conductor and due to the fact that an impedance variation causes different reflections of the voltage wave, it is possible

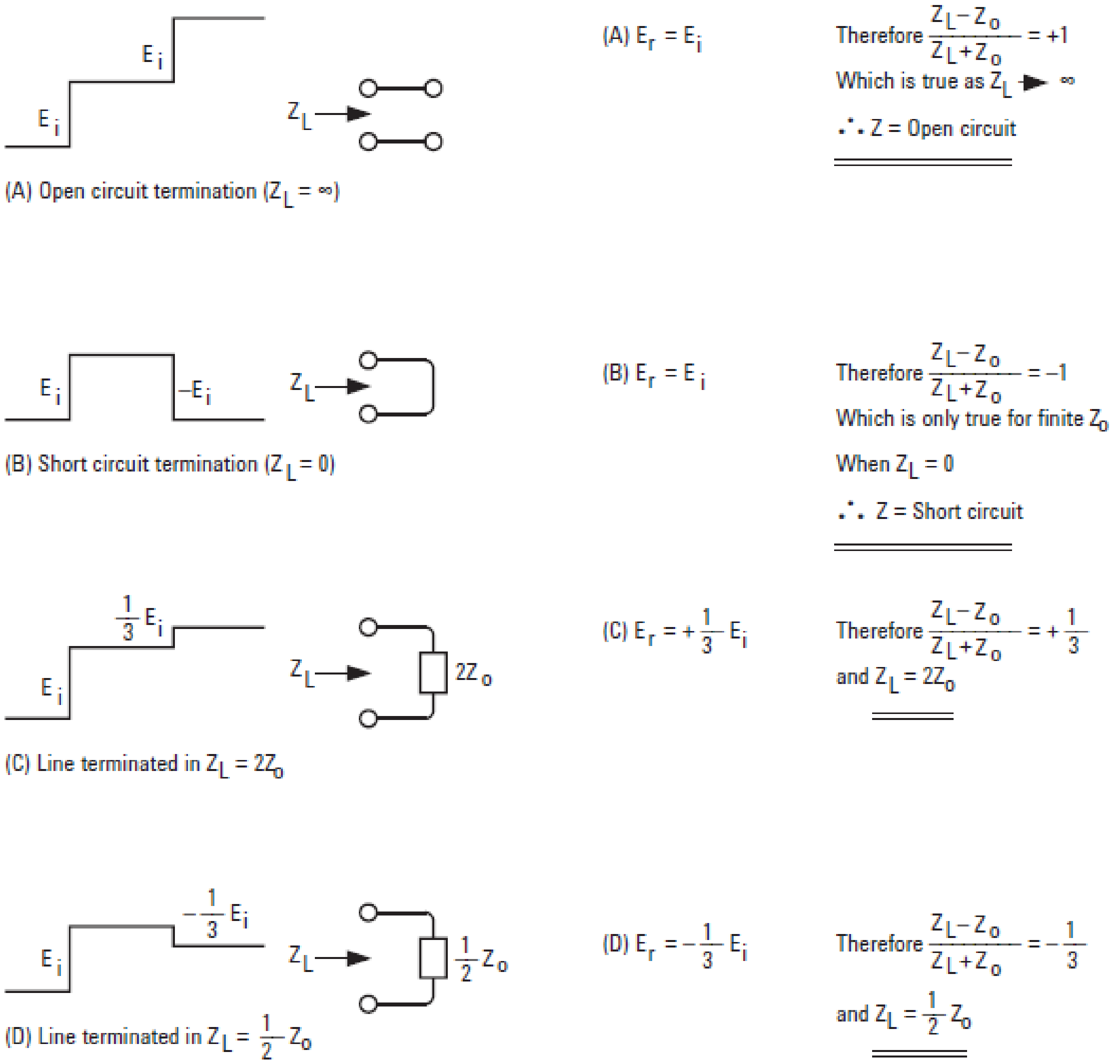

Figure 6-2: TDR reflectograms for typical loads [5]

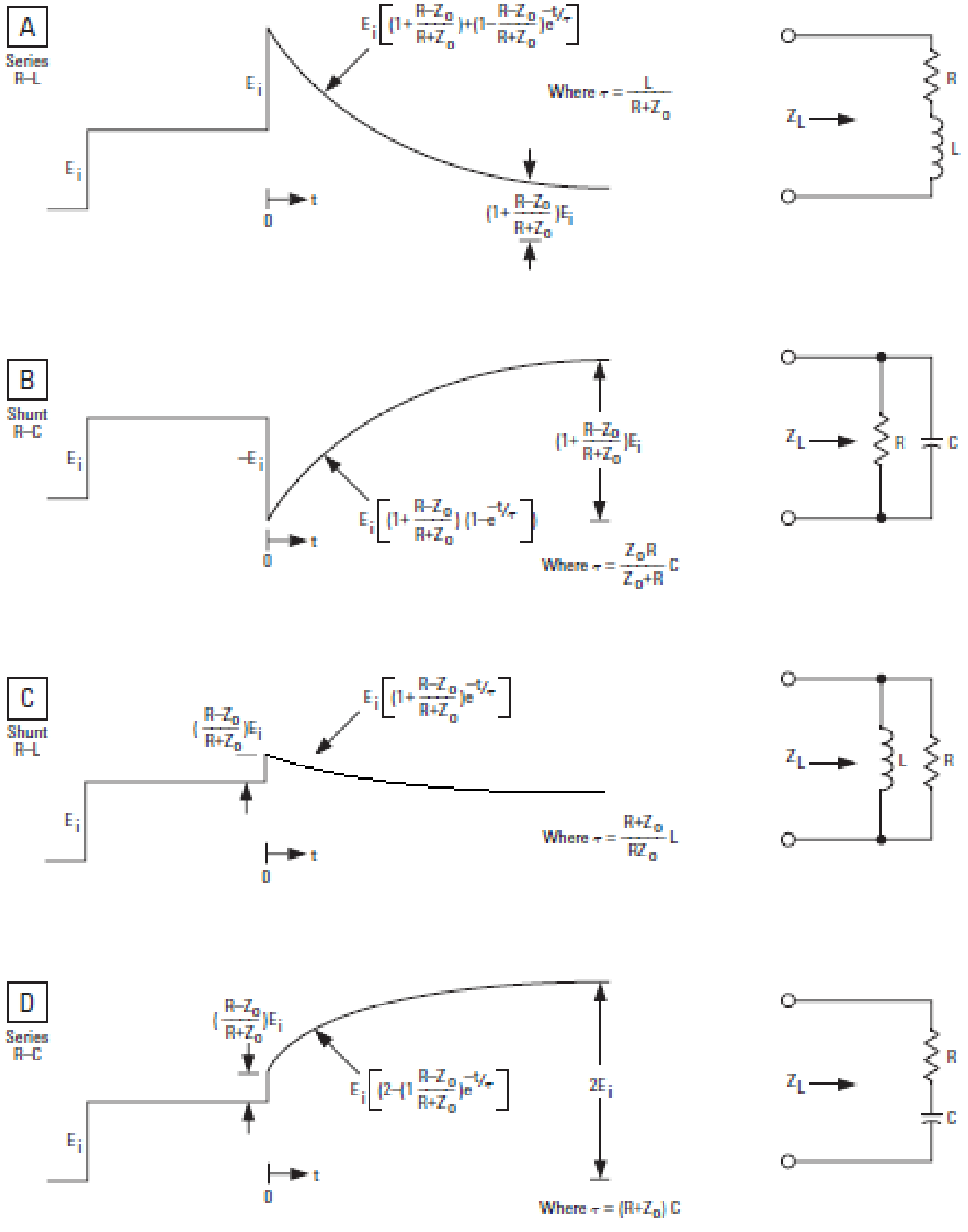

Figure 6-3: TDR reflectograms for complex load impedances [5]

to determine the response of a cable to this signal. Since in a fault condition an impedance variation occurs which gives a different response than the one of a healthy wire, the fault condition and its spatial location D in a cable could be determined:

$$D = v_\rho \frac{T}{2} \tag{6.8}$$

T represents the transit time form the monitoring point to the impedance mismatch and back.

Soft Fault Problem

[21] shows the problem of detecting soft faults with typical reflectometry techniques. Due to the small impedance changes of the soft faults, the peaks in the reflectograms are buried in the noise level and are virtually undetectable. The peak value for a TDR output can be observed for different faults in figure 6-4.

6.2.2 Spread Spectrum TDR

To increase the energy of the pulse used in TDR and make it more immune to noise, the input signal is spread over the spectrum in baseband (STDR) and modulated (SSTDR). The signals that may be buried in noise are identifiable through cross-correlation. [31] [19] [40]

STDR and SSTDR are based on the fact that portions of voltage wave that is inserted on to the network under test are reflected by discontinuities. When the reflected signal is correlated with a copy of the injected signal, peaks appear at locations correspondent to the impedance mismatches. [31]

The autocorrelation of the input signal shown in the upper part of the figure 6-5 will give a shape of the peaks as shown in the lower part of the same figure.

The PN Code used in SSTDR can be very small compared to the signals on the wires it is used on and has to be synchronised with the modulating sine-wave. Although it is small in magnitude, it is quite long (1023 bits in some cases) and has

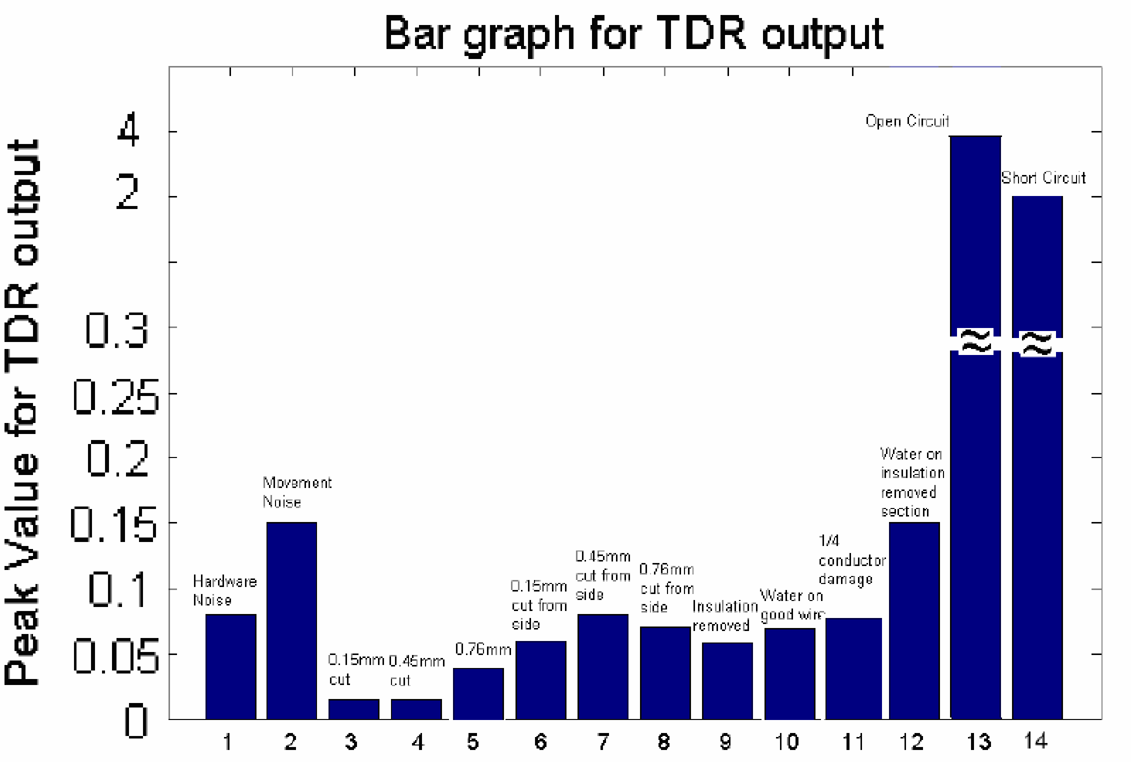

Figure 6-4: Peak values for different frays. (1) Hardware Noise, (2) Movement noise, (3) 0.15 mm cut from top, (4) 0.45 mm cut from top, (5) 0.76 mm cut from top, (6) 0.15 mm cut from side, (7) 0.45 mm cut from side, (8) 0.75 mm cut from side, (9) insulation removed from single side, (10) water on good wire, (11) 1/4 conductor damaged, (12) water on cable with insulation removed, (13) Open Circuit, (14) Short Circuit. [21]

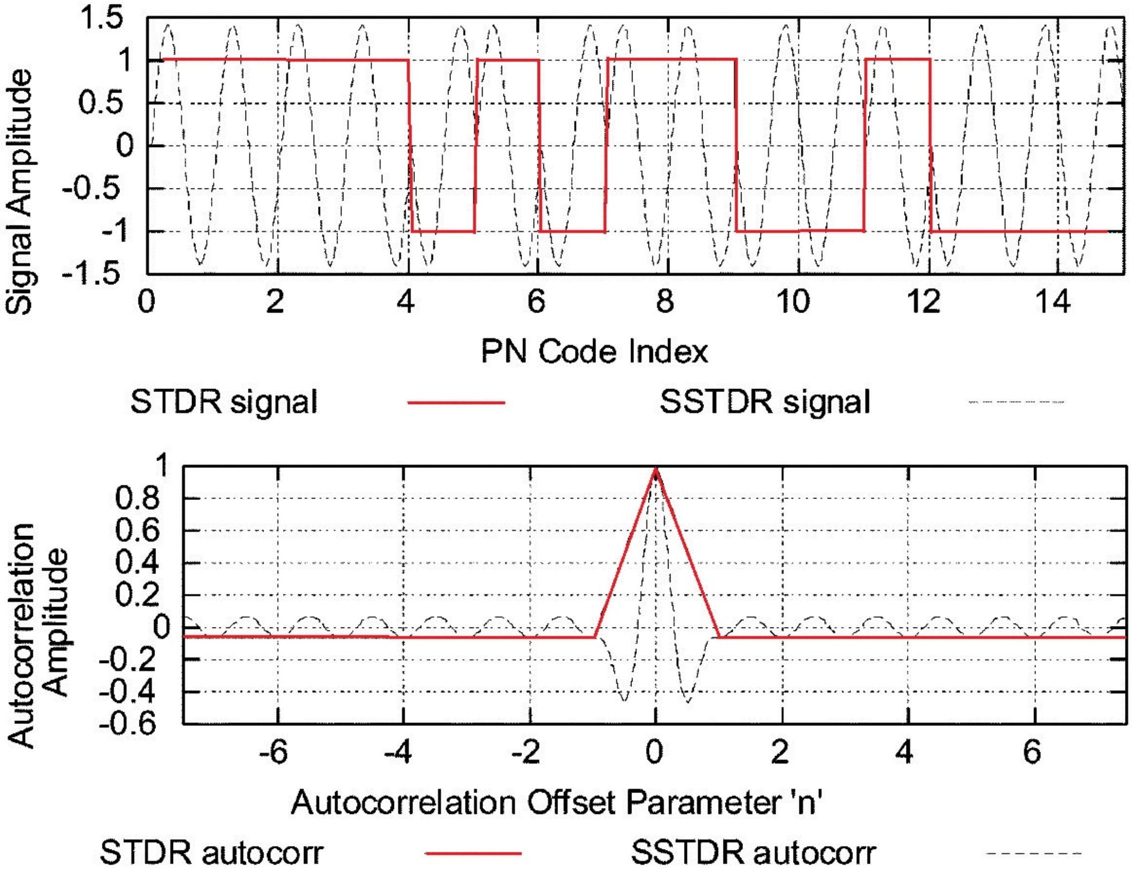

Figure 6-5: SSTDR stimulus and autocorrelation [31]

a distinct repeatable pattern that makes it recognisable. The frequency of a PN code is usually between 30 and 100MHz. The chosen PN type of code depends on the nature of the application. The ML (Maximum Length) Codes have low side-lobes in the autocorrelation and are optimal for use when only one code is needed. The Kasami Code is the next best one due to its autocorrelation properties. Codes such as the Gold Code can be used if the number of tests exceeds the number of codes in the Kasami test. [31] [32]

An advantage of SSTDR over STDR is that the peaks that are obtained through cross-correlation are sharper and makes it therefore very accurate in detection of faults on live wires. The height of these peaks depends on the length, type and integration time of the PN code. [32]

The fact that it can be run on live wires gives S/STDR a big advantage in regards with other reflectometry techniques. This allows it to store a dynamic baseline [32], or dynamic reference profile. Loads that turn on or off will appear as changes on such a baseline, but can be distinguished from the faults if additional sensors are placed at the loads or as in the case of cars, there is a control system that monitors all loads. Probably one of the biggest advantage of SSTDR is the possibility of detecting the arc faults and short intermittent faults. [16] This along the fact that it can be implemented on a small embedded chip makes it a solid competitor for the detection of faults in electric wiring.

6.3 Signal Processing Techniques

6.3.1 Wavelets

A wavelet is a waveform with a limited duration and a zero average value. Wavelets allow a time domain signal to be decomposed into a new set of basis functions. [1] There are many types of wavelets such as the: Complex Gaussian wavelet, Complex Morlet wavelet, Coiflet wavelet, Daubechies wavelet, Mexican hat wavelet, Meyer

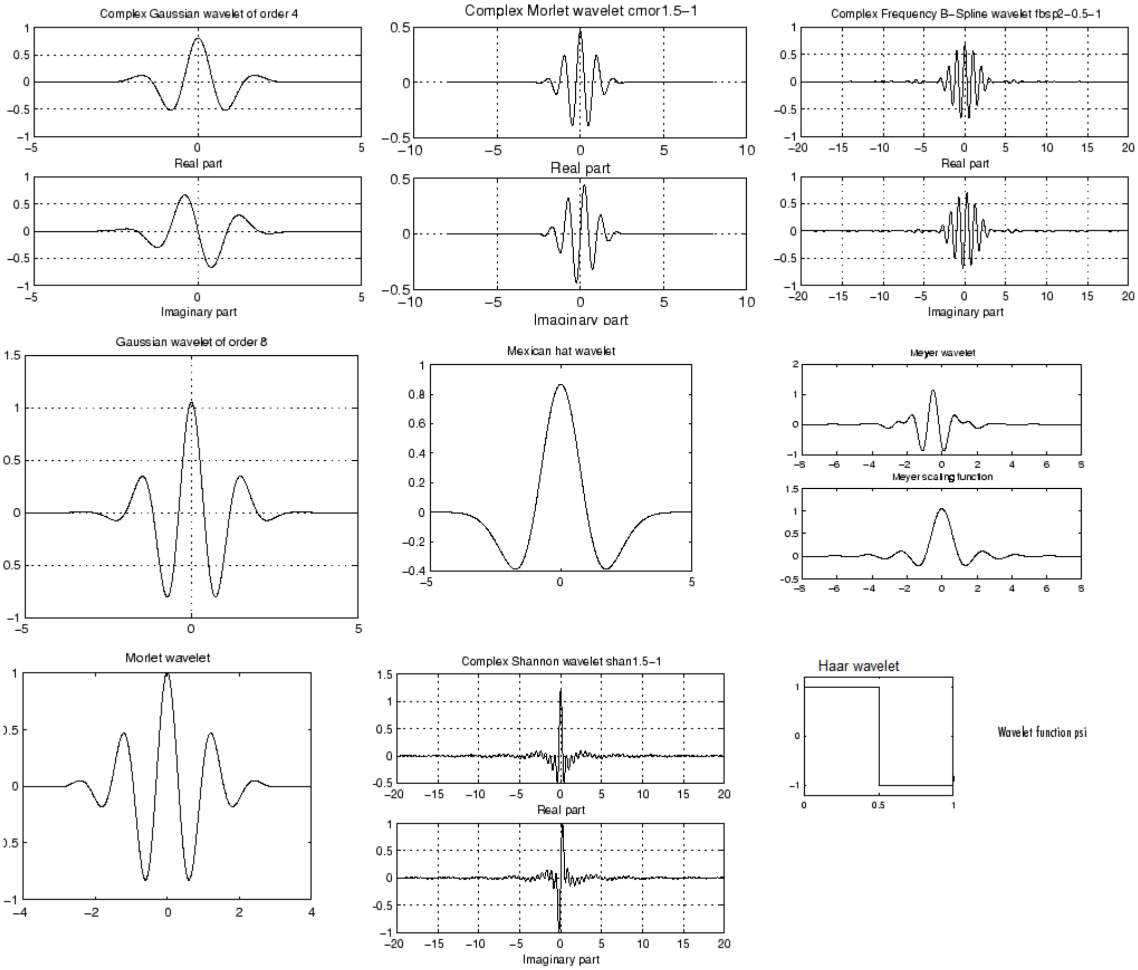

Figure 6-6: Examples of wavelets [4]

wavelet, Morlet wavelet, Complex Shannon wavelet or Symlet wavelet. The Haar wavelet is the simplest wavelet and is discontinuous, resembling a step function.

Wavelet analysis allows the capture of different aspects of a signal such as the low-frequency content and the high frequency one. Low frequency and high frequency components of the signal can be separated in terms of coefficients. This is done through the decomposition of the time domain signal. Broken into frequency bands that are an octave apart, the scales of a wavelet transform are arranged such that the last one contains the upper half of the frequency content, the one before that, the preceding quarter of frequency content and so on. [1]

There are two main types of 1 dimensional wavelets for the needed DSP. The

CWT (Continuous Wavelet Transform) and the DWT (Discrete Wavelet Transform). Unlike the discrete wavelet transform, the CWT can operate at every scale, from that of the original signal up to some maximum scale that one can determine by trading off the need for detailed analysis with available computational power.

6.3.2 Cross - Correlation

The Cross-Correlation measures the similarity of two waveforms as a function of time delay applied to one of them, which makes it particularly interesting in TDR where the reflected waveform is delayed in terms of the inserted one.

The cross-correlation helps reduce many irrelevant peaks/oscillations in the refelctogram when applying it with the stimulus signal. [29]

Cross-correlation is used in most of the reflectometry techniques (TDR, TFDR, SSTDR, etc.). In TDR it can be useful to reduce the irrelevant peaks. In SSTDR the signals that may be buried in noise are identifiable through cross-correlation. [31]

Chapter 7

Proposed Solutions

A model for TDR and SSTDR was created and a new SSTDR-FSK technique was developed. Experiments were done in CAN twisted pair wires and coaxial cables of different lengths and the models for TDR were validated through experimental measurements.

Different sample rates were used and the possibility of using existent car signals such as the CAN messages as stimulus was investigated. More loads and faults were tried out experimentally.

A DSP algorithm based on the *haar* wavelet, that automatically detects the edge of a voltage hybrid pulse-step for TDR and gives the distance measurement to a hard fault was developed.

7.1 Experiment and Simulations

To prepare the experiment, the set-up shown in figure 7-1 was used. The TDR measurements were done with the use of a voltage step with a slow rise time and with a hybrid pulse-step signal. These two signals were available from a Tegam 2711A automatic wave generator (AWG) and were chosen out of the available signals as the most appropriate for TDR measurements. Most of the measurements were done on open end wires as this is one of the most common faults in the automotive sector, when connectors move around due to vibrations.

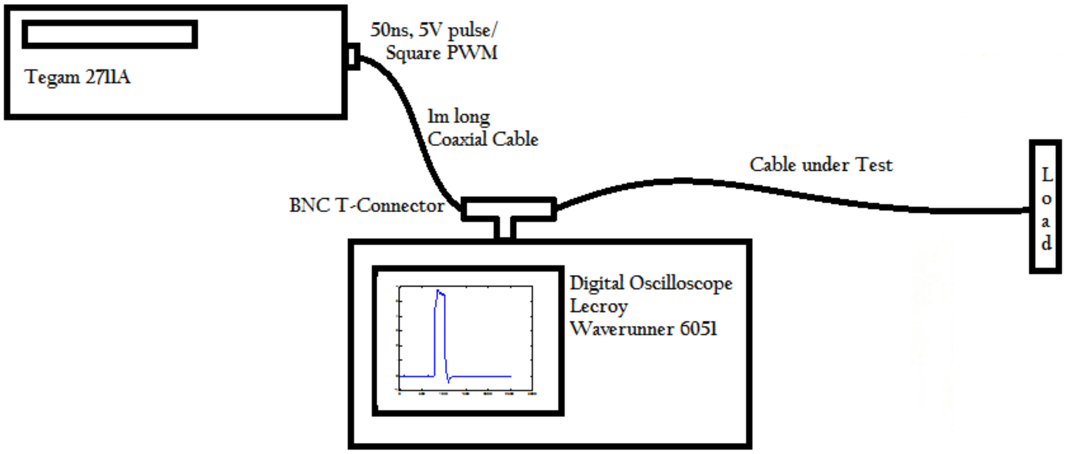

Figure 7-1: TDR Experimental set-up

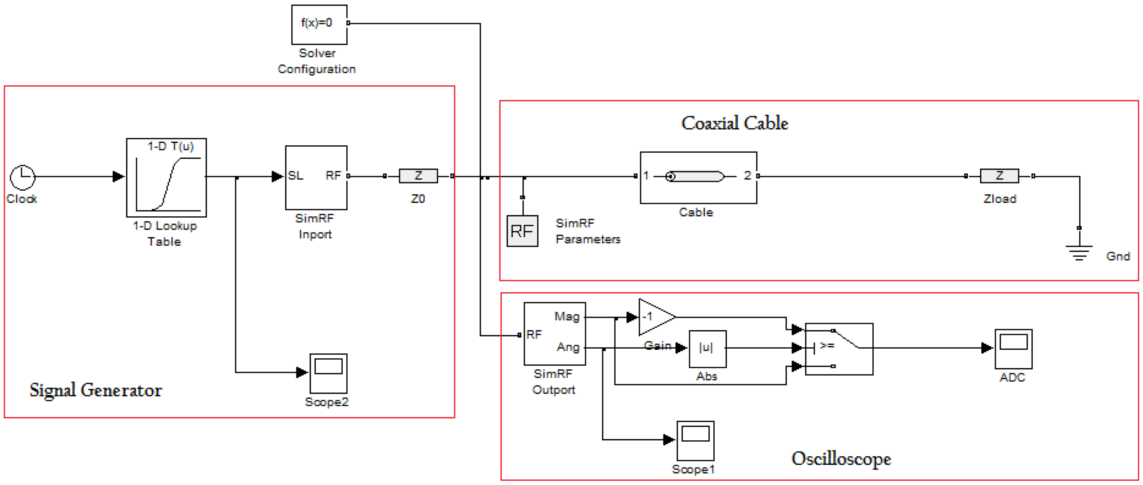

Figure 7-2: TDR Simulink model of the experiment

7.1.1 Coaxial Cable

The first experiments were made on a coaxial 50Ω impedance cable. This was connected to the BNC T-Connector as seen in figure 7-1 for the experimental set-up and in figure 7-2 for the simulation model. The two available signals were used as stimulus signals and compared to the results the simulation model (figure 7-1) gave. As input signal for this model, the recorded stimuli from the signal generator were used.

The results of this experiment and the validity of the coaxial cable model can be seen for the two stimuli in figures 7-3 and 7-4. For the coaxial cable a delay based

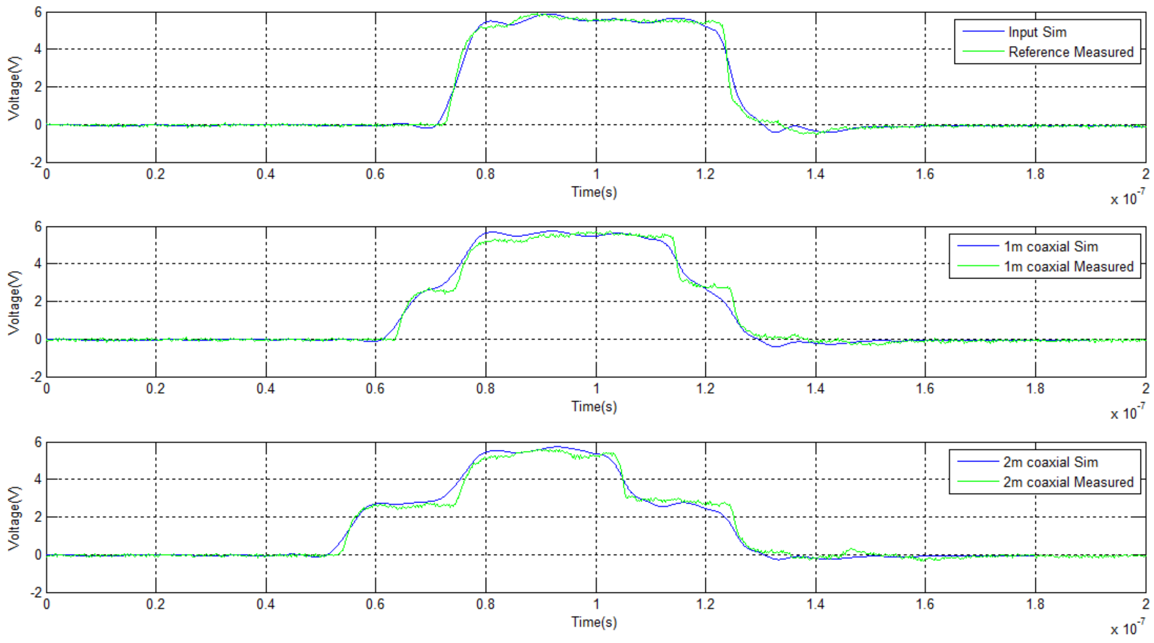

Figure 7-3: TDR Experiment and Comparison for a coaxial open end cable with a 50ns pulse input signal

and lossy model with a 50Ω characteristic impedance and a 5ns/m transmission delay was used.

Another experiment for the step with limited rise time and different terminators is seen in figure 7-5.

The simulation closely matches the experimental results. Due to the limitation of available coaxial cables for the experiment and the fact that this type of cable is not that common in cars, the rest of the experiments were done on twisted pair CAN cables. These are amongst the thinnest cables on vehicles and therefore subjected to faults. They are also very common in vehicles and therefore more attention was given on this type of cables.

Also worth mentioning is that this first experiments showed that the pulse stimulus signals gives more noticeable reflections. That is why it was chosen as the preferred signal in the experiments to follow.

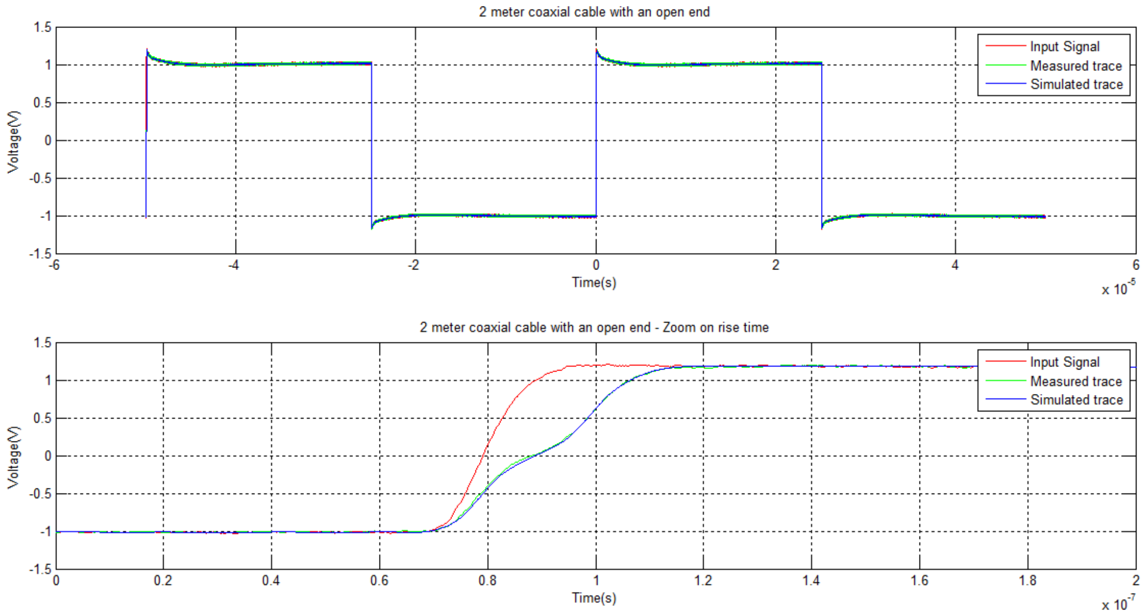

Figure 7-4: TDR Experiment and Comparison for a coaxial open end cable with a square signal with slow rise time input signal

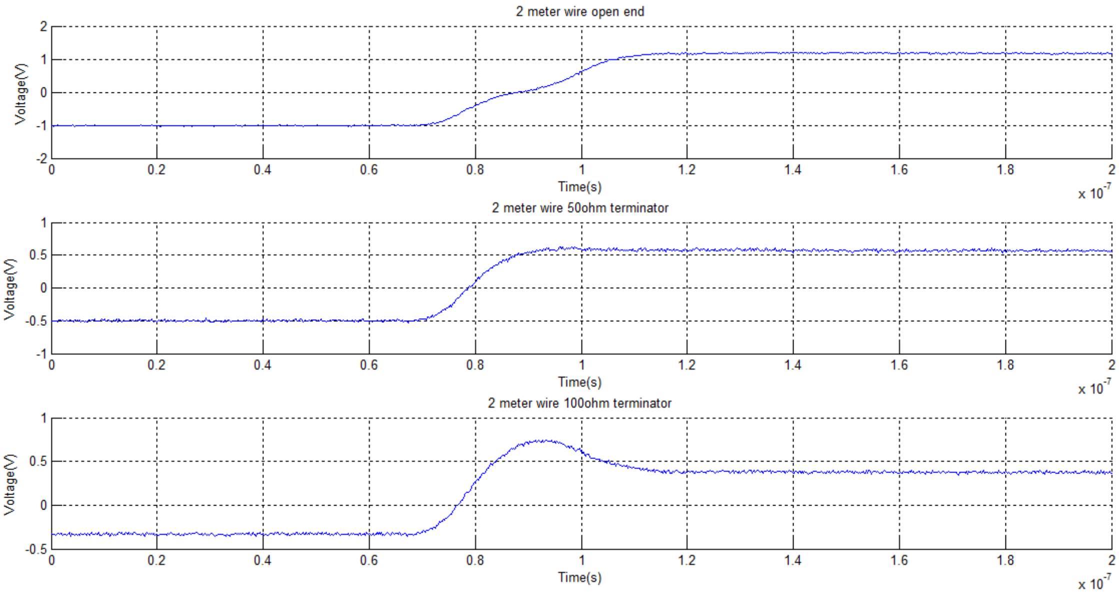

Figure 7-5: TDR Experiment for a coaxial open end cable with a square signal with slow rise time input signal; different terminators

7.1.2 CAN twisted-pair Cable

The CAN twisted pair cables have a 120Ω characteristic impedance and a transmission delay of 5ns/m [14] [15]. In order to connect this type of cable to the T-connector, a BNC connector with two short wires (6cm long) and clamps was fabricated.

Experiments with the two available waveforms were made as shown in the following two subsections.

50ns Square Pulse

The 50ns voltage pulse was used as stimulus and the distance to an open circuit fault was automatically measured with a wavelet algorithm and then compared to the simulation model. The obtained waveforms are similar to the ones in [7], but the pulse is about 10 times shorter in time and the lengths of the cables accordingly. The DSP (Digital Signal Processing) results were obtained in Matlab.

The *haar* continuous wavelets were used for detecting the edges, that is the reflections of the impedance changes. This was chosen based on the arguments shown in section 6.3.1. The 32 *haar* wavelets can be seen in the upper part of figure 7-6. In the bottom part, only the 32nd wavelet was considered, the one that has the highest amplitude. It was empirically shown that for a twisted pair CAN cable and a hybrid pulse-step stimulus signal, the first two negative and positive peaks are higher than 20% of the maximum amplitude of the *haar* wavelet.

Based on this edge detection algorithm, the distance to an open circuit was experimentally measured. The simulation model for a CAN twisted pair wire was compared and the results can be seen for a cable of 2.5m in figure 7-7.

The algorithm that measures the distance between the first two peaks of the wavelet returned a length of precisely 2.5m for the experimentally measured trace, and a 2.49m length for the simulation obtained trace. This distance corresponds to the distance up to the reflection point, the open end in this case. More cable lengths were measured, from 0.5m up to 5m with an incremental step of half a meter.

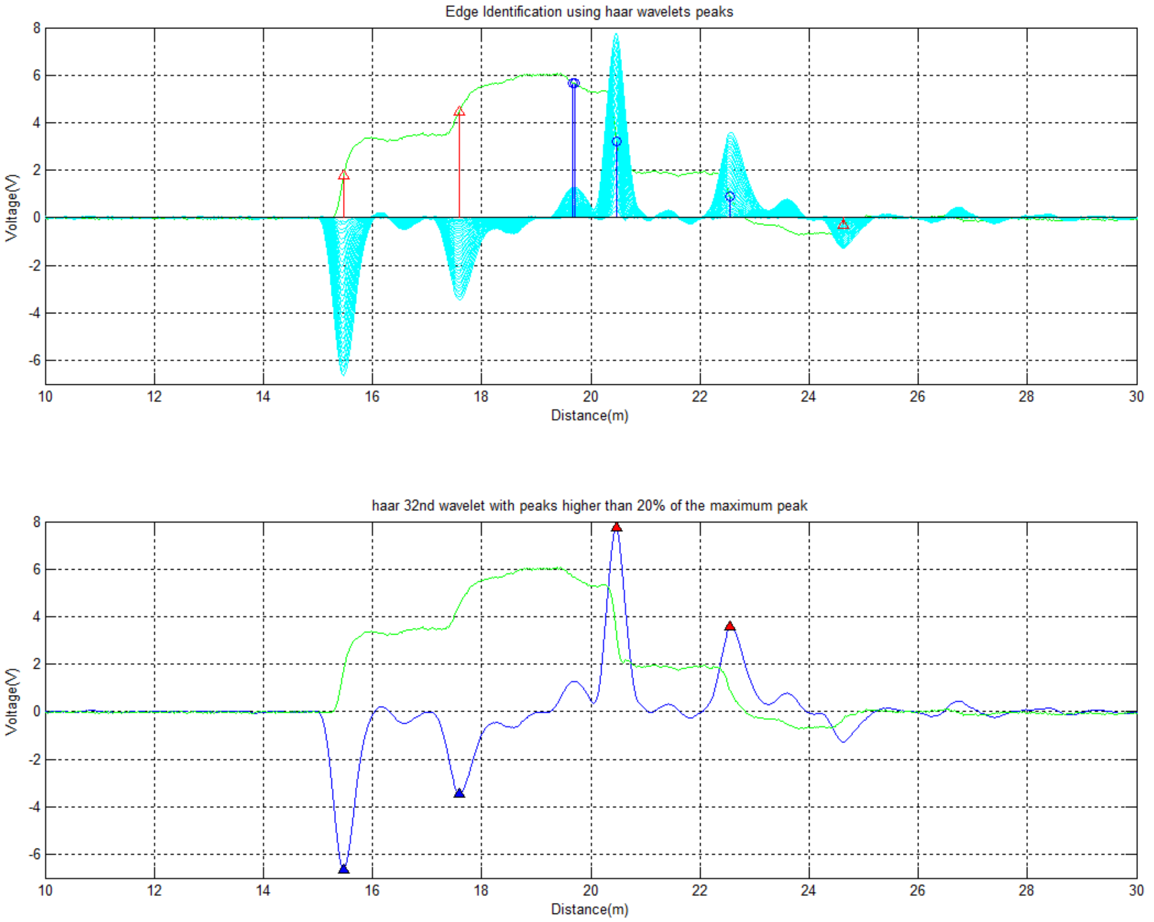

Figure 7-6: Haar Wavelets for edge identification

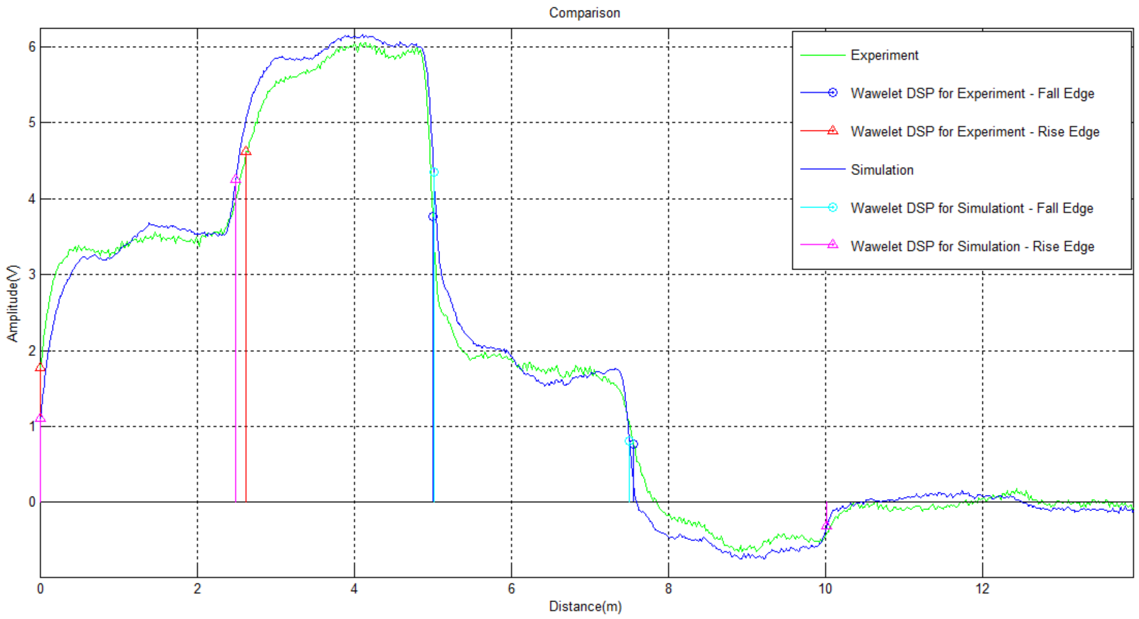

Figure 7-7: Experiment and Simulation Comparison; automatic edge detection algorithm

Once having shown that the simulation model is accurate and according to the reality, more simulations were ran systematically and traces for cables between 0.1 and 10m with a incremental step of 0.1m were obtained.

The errors of the measurement of the algorithm for the experimental and the simulation results are shown in figures 7-8, 7-9 and 7-10.

When evaluating figures 7-8 and 7-9 of the experiment and simulation, one notices the higher errors when measuring cables shorter than 1m and of around 5m. The problem of spatial aliasing was therefore discovered: the width of the pulse is of about 50ns and the transmission delay of the CAN twisted pair cable being of 5ns/m, means that when the wave travels 10 meters, spatial aliasing will become problematic. This happens for a cable of 5 meters long where the wave travels for 10 meters forwards and backwards. The simulation and experimental measurements for such a cable of 5m are shown in figure 7-11.

One solution of solving this problem, for the implementation of a product, would be to dynamically change the pulse duration in order to avoid any alias combination

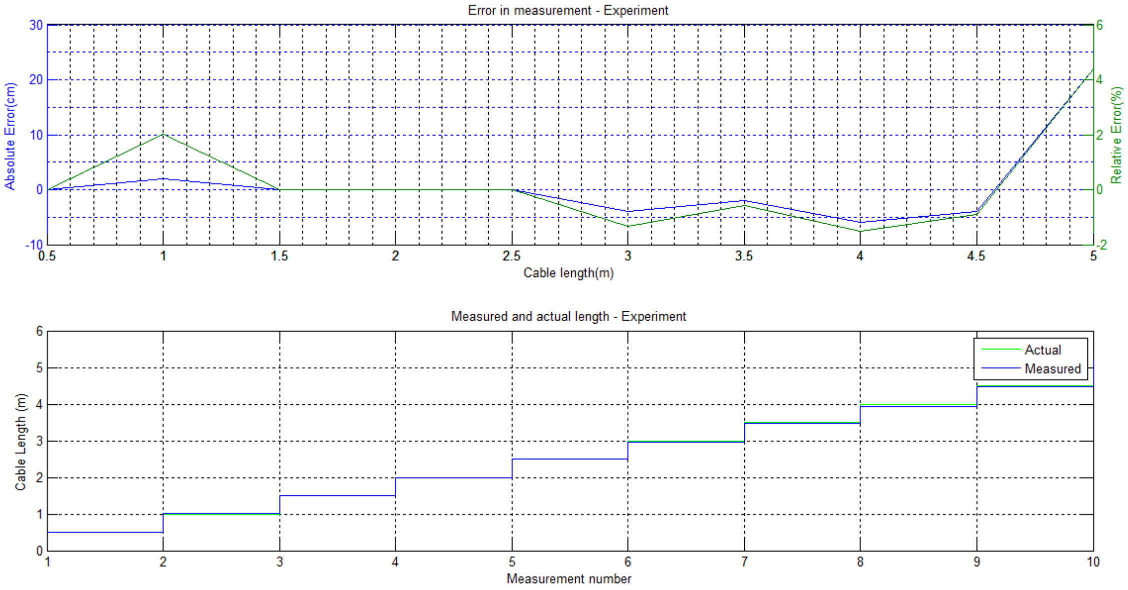

Figure 7-8: Experiment - Error in percentage and absolute for the measurement algorithm - Real length vs. measured length

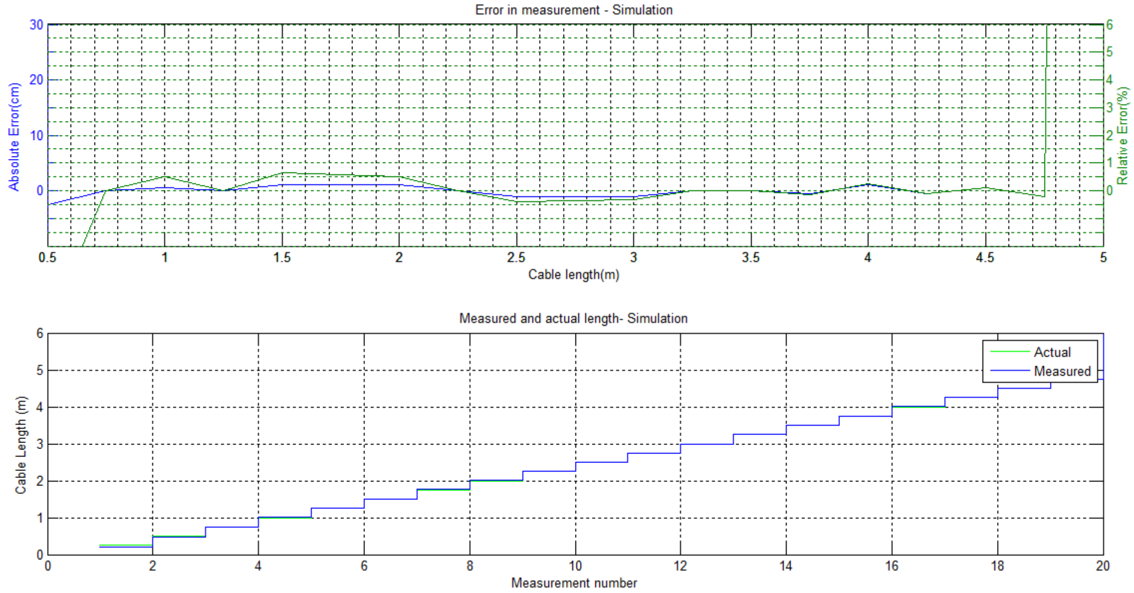

Figure 7-9: Simulation - Error in percentage and absolute for the measurement algorithm - Real length vs. measured length

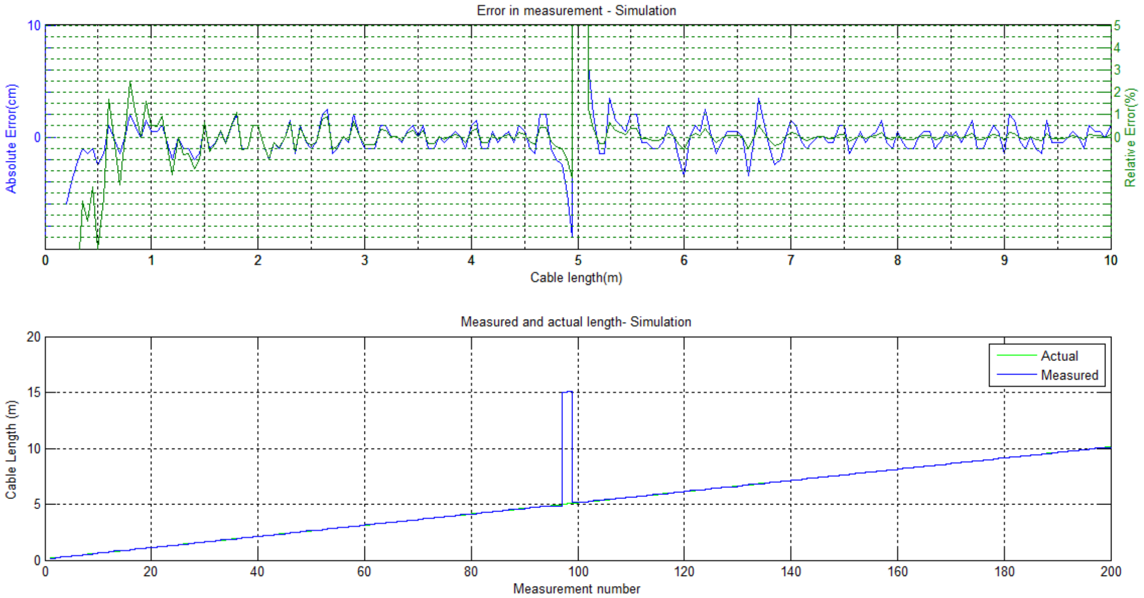

Figure 7-10: Simulation - Error in percentage and absolute for the measurement algorithm - Real length vs. measured length

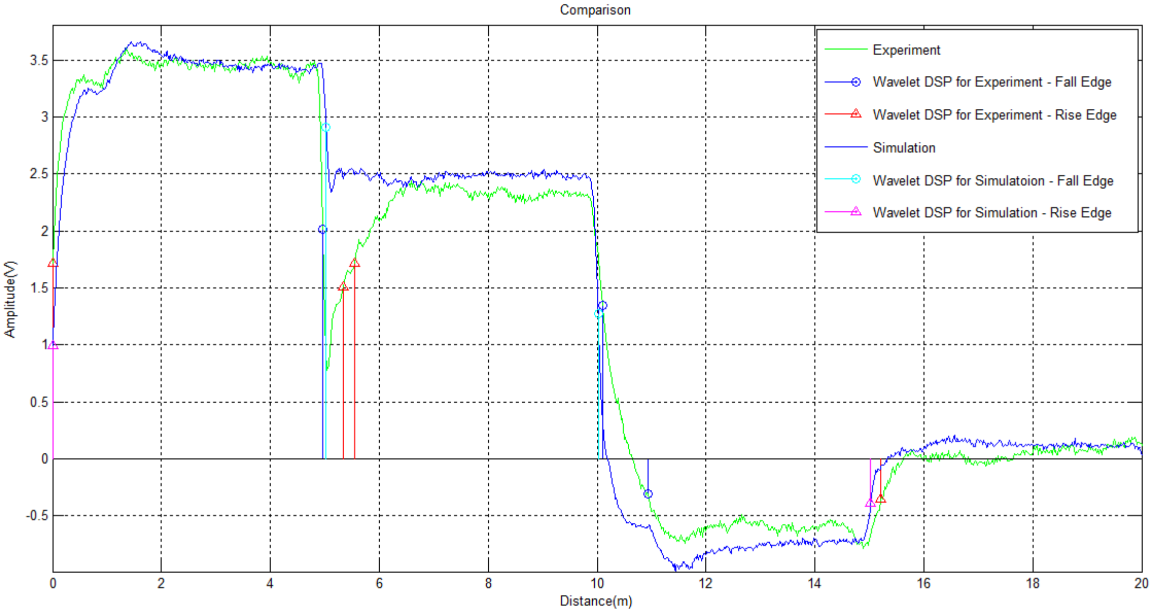

Figure 7-11: Experiment and Simulation Comparison; automatic edge detection algorithm - Spatial aliasing

of pulse duration/cable length.

Another solution would be using a longer pulse duration then the cable length, as the cables in a vehicle are of known values and limited distance. That would lead only to waveforms that are similar to the ones in figure 7-7, and waveforms where the whole pulse is reflected as the ones in figure 7-11 wouldn't exist. The method would be similar to the ones where voltage steps are used to evaluate the state of the wiring.

Step with limited rise time (PWM)

For the square signal (PWM) shown in the upper part of figure 7-4, more measurements for a CAN twisted-pair cable were made in which different components were used as loads at the end of a 5m wire.

The offset from the signal generator was used to introduce a DC level. The measured results are shown in figure 7-12.

In this case a profile of a signal in a wire without a fault would be similar to the one of the matched impedance in figure 7-12. Worth mentioning is that the differences from this reference profile (healthy wiring) that may be similar to the other profiles from the same figures could be identified even with basic digital signalling processing techniques.

7.1.3 Grounding Cable

Many cabling faults in cars have as root cause the inappropriate installation of the grounding cables. Sometimes, during fabrication a thin layer of non-conducting paint is wrongfully sprayed over the connection point where the grounding cables are attached through screws, bolts or studs. This leads to an increased impedance of the connection point. Through vibrations, it may happen that a cable moves around and the circuit opens for a short time.

This subsection shows an experimental result that validates the possible use of time domain reflectometry for verifying the correct instalment of grounding cables on

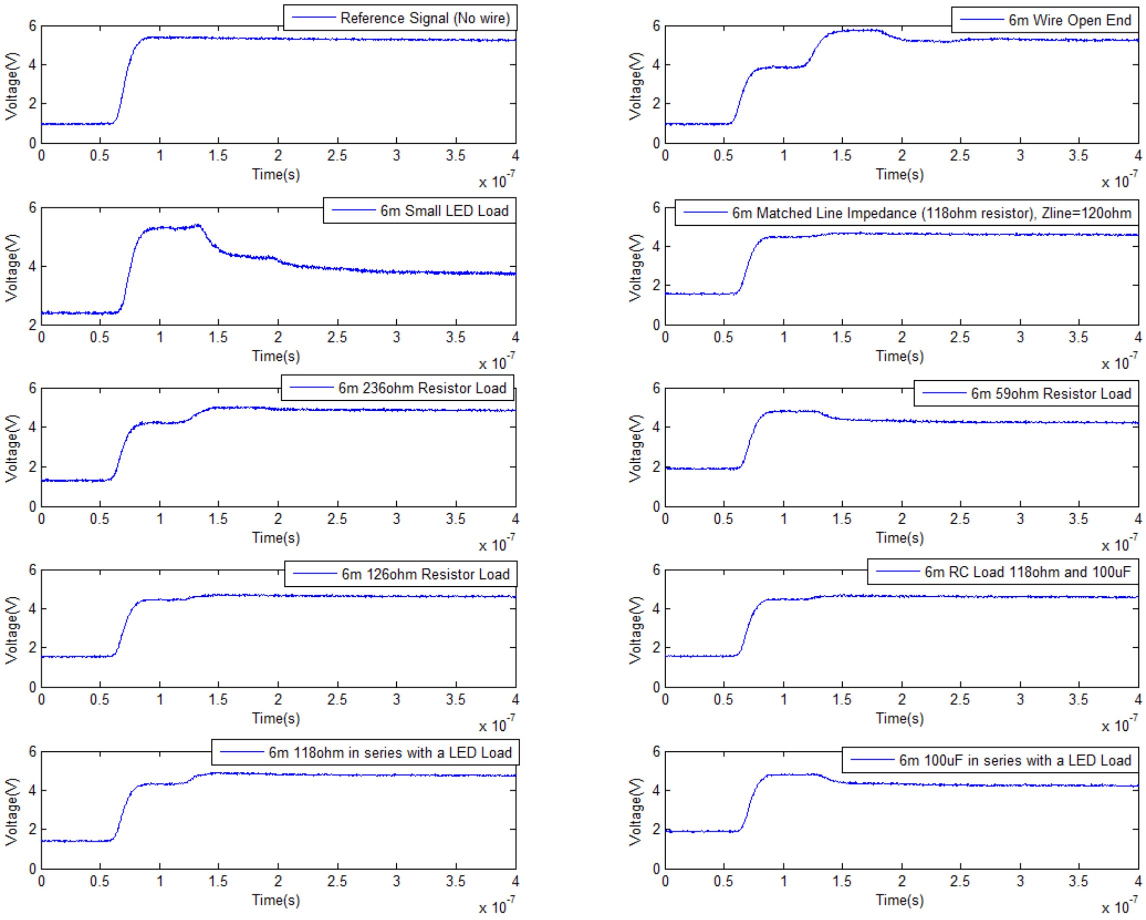

Figure 7-12: Twisted pair 5m cable with an offset PWM pulse and different loads

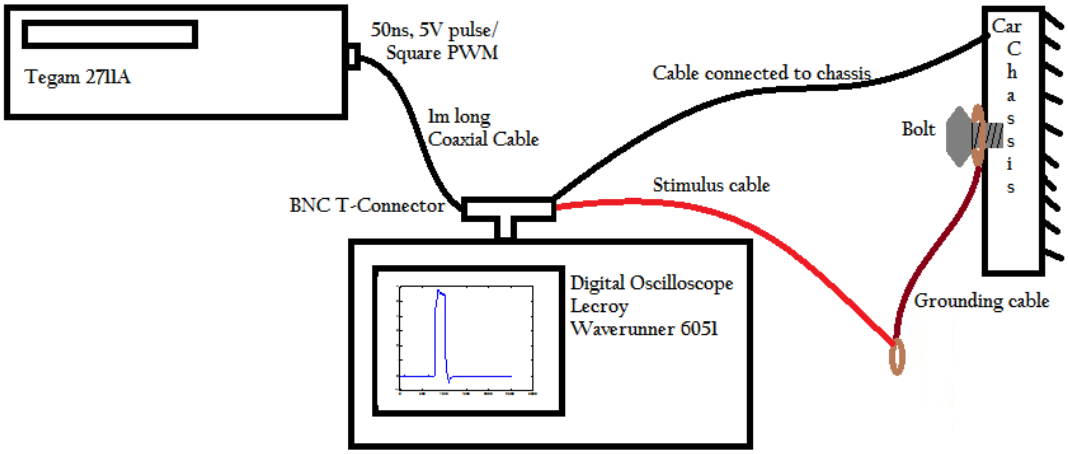

Figure 7-13: Experimental set-up for ground connection testing

vehicles.

To prove that TDR could be used for this, an experimental set-up similar to the one in figure 7-13 was prepared. An accessible grounding point connection was found and one terminal of the grounding cable was disconnected from it's original point and connected through a clamp to the TDR set-up. The 50ns pulse stimulus was inserted in this cable and the reflexions were observed on the oscilloscope. The ground cable of the oscilloscope was connected to the car chassis.

After measuring the profile for a good ground connection, a profile similar to the one of a short-circuit or cable terminated with a very small load, the bolt was loosened and paper tape was placed on the connection point in order to simulate a thin layer of paint as one would find on a faulty grounding connection.

In a properly attached ground connection, the current flows to the chassis not only through the sides of the ring pad connection (one on the chassis and one on the bolt), but also through the inside part of the ring that is in contact with the bolt. When there is paint present on the chassis and bolt, the connection could be made only through the inner side of the ring connection. If this occurs, the chances of a fault to appear are increased.

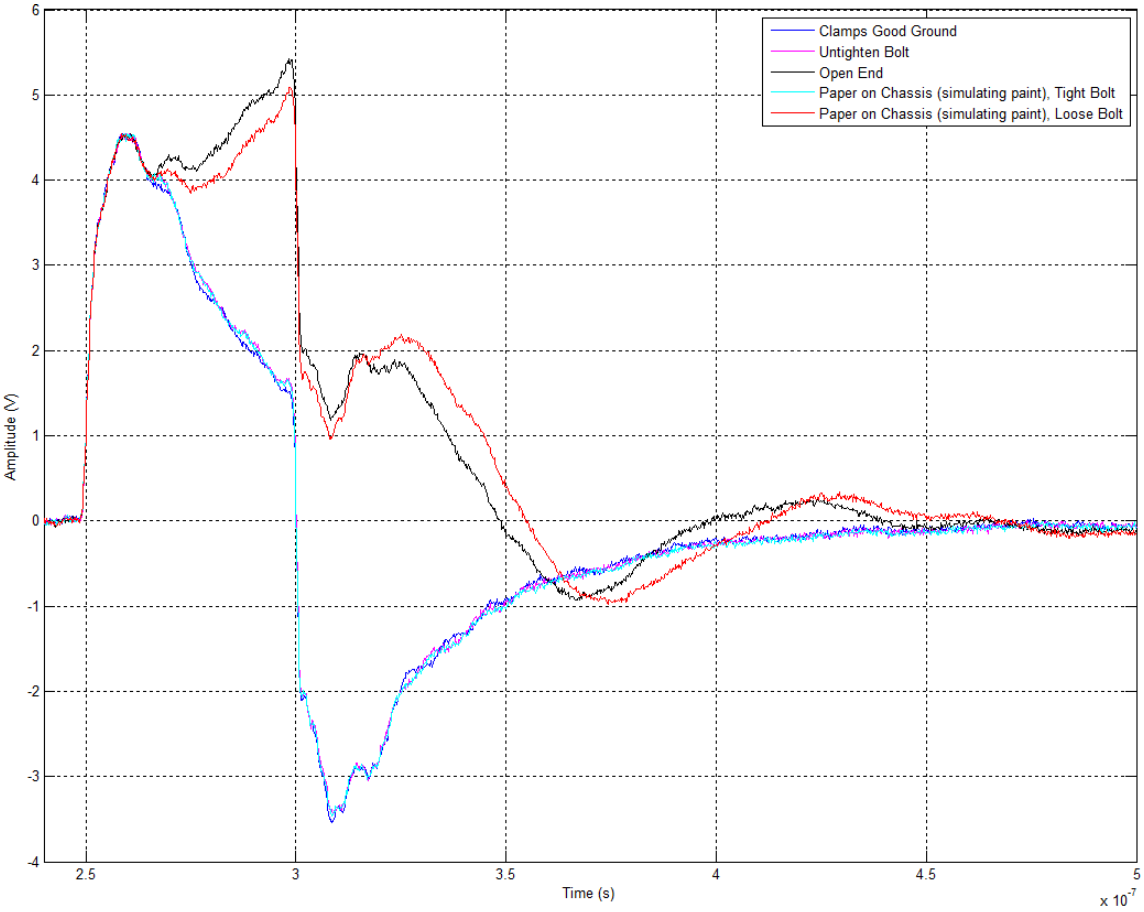

Figure 7-14: Grounding cable experiment

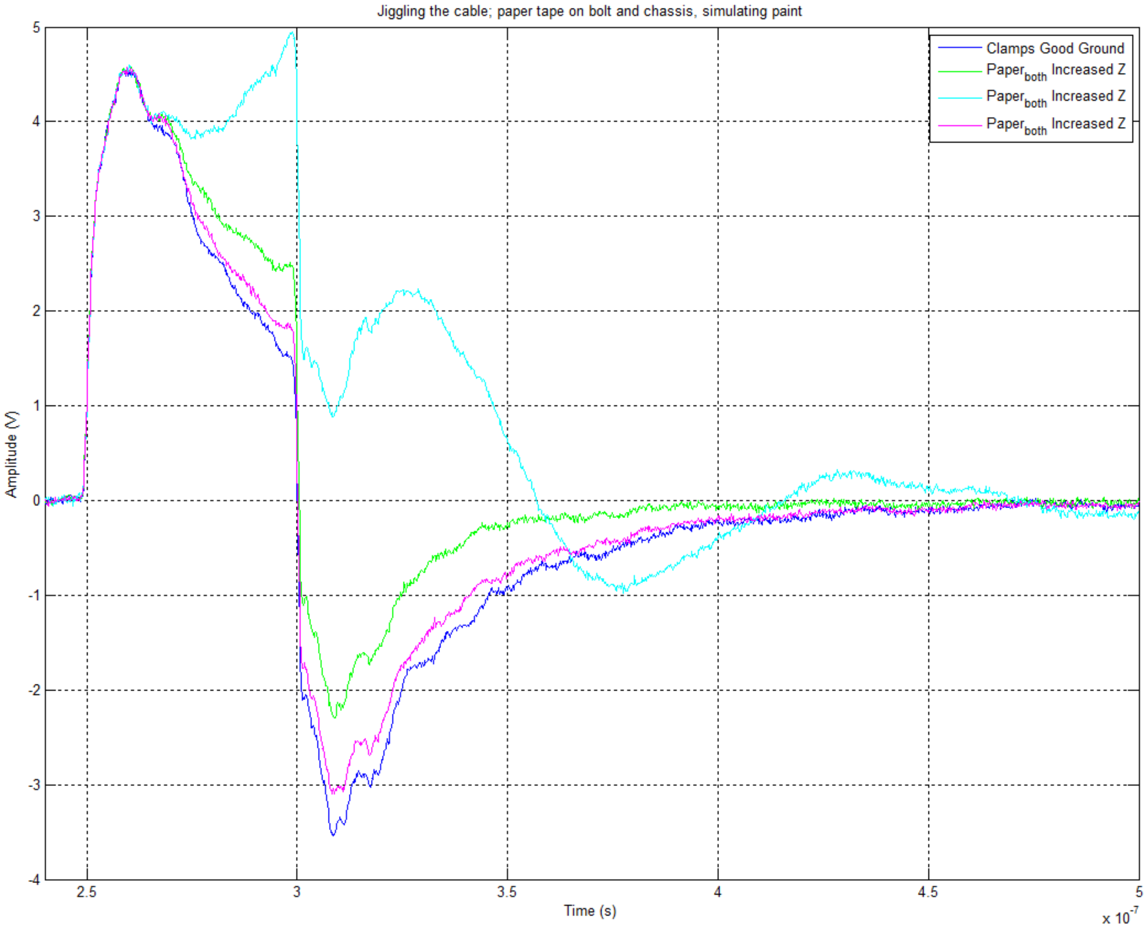

Figure 7-15: Grounding cable experiment

In figure 7-14 the profiles for the good connection, loosen bolt and a tight bolt with paper tape on the chassis and bolt are very much alike. Differencing one from the other would be almost impossible. This happens due to the fact that the current still circulates through the inside part of the ring connection. In this case, even with paint present on both the bolt and chassis, the grounding would still be satisfactory. However the ring pad being consistently bigger than the bolt, profiles similar to the ones in figure 7-15 may occur as sometimes the inner part of the ring pad connection may not contact the bolt.

In such a condition, the faulty connection is easily noticeable. In the measurements shown in figure 7-15, the bolt was fastened almost to it's normal position but the terminal could be moved if sufficient force was applied. Through moving the grounding terminal, the connection between the bolt and the ring connector changed and a faulty connection point was made.

Figure 7-16 shows the simulation traces for an increased contact impedance. Through comparing it with figures 7-15 and 7-14, a reference of what the impedance of a faulty connection profile might be when conductive paint is present on the connection point of a grounding cable is obtained.

To sum up and conclude, there are two parameters that favour a faulty ground connection: the first one is the paint on the connection point and the second one is the placement of the ring connector pad. The position of this pad is not a controlled parameter especially in a rich vibration environment and with paint present on the connection point, faults are more likely to occur. These could be discovered if a continuous monitoring is done.

TDR could also help detect the increased impedances as seen in 7-15, which wouldn't be normally detected with common conductivity testing methods. In this figure, the green and magenta profiles aren't detectable through conductivity methods, but show increased impedances that could lead to intermittent or even continuous hard faults.

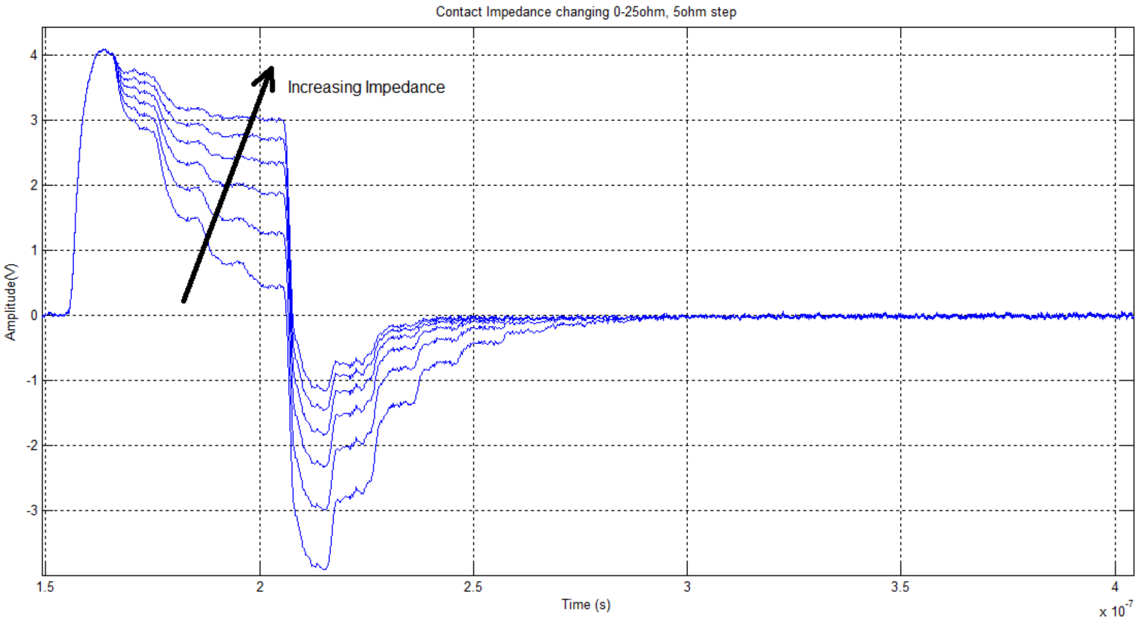

Figure 7-16: Faulty connection increased impedance simulation: 0Ω, 5Ω, 10Ω, 15Ω, 20Ω, 25Ω connection point impedance

7.1.4 Other Experiments

More experiments were made in which the current was measured (instead of the voltage), CAN signals from a SEAT Leon car were investigated as a possible source for a stimulus signal, different sampling rates were tried out and the problem of soft faults with TDR was checked.

Current Measurement

Measuring the current is important as many networks already have current sensors installed. In order to do this measurement, the probes of the oscilloscope were used and the voltage drop on an additional resistor was measured. The current, proportional to this voltage was plotted according to figure 7-17. A simulation model was built to try to reproduce the experiment. However, because the impedance of the probe wires was unknown, the results don't match perfectly, but a similarity of the two is still clearly visible.

The current was measured for a 5m long twisted pair wire with a matched impedance, an open connector and a short-circuit at the end. The simulation was conducted for

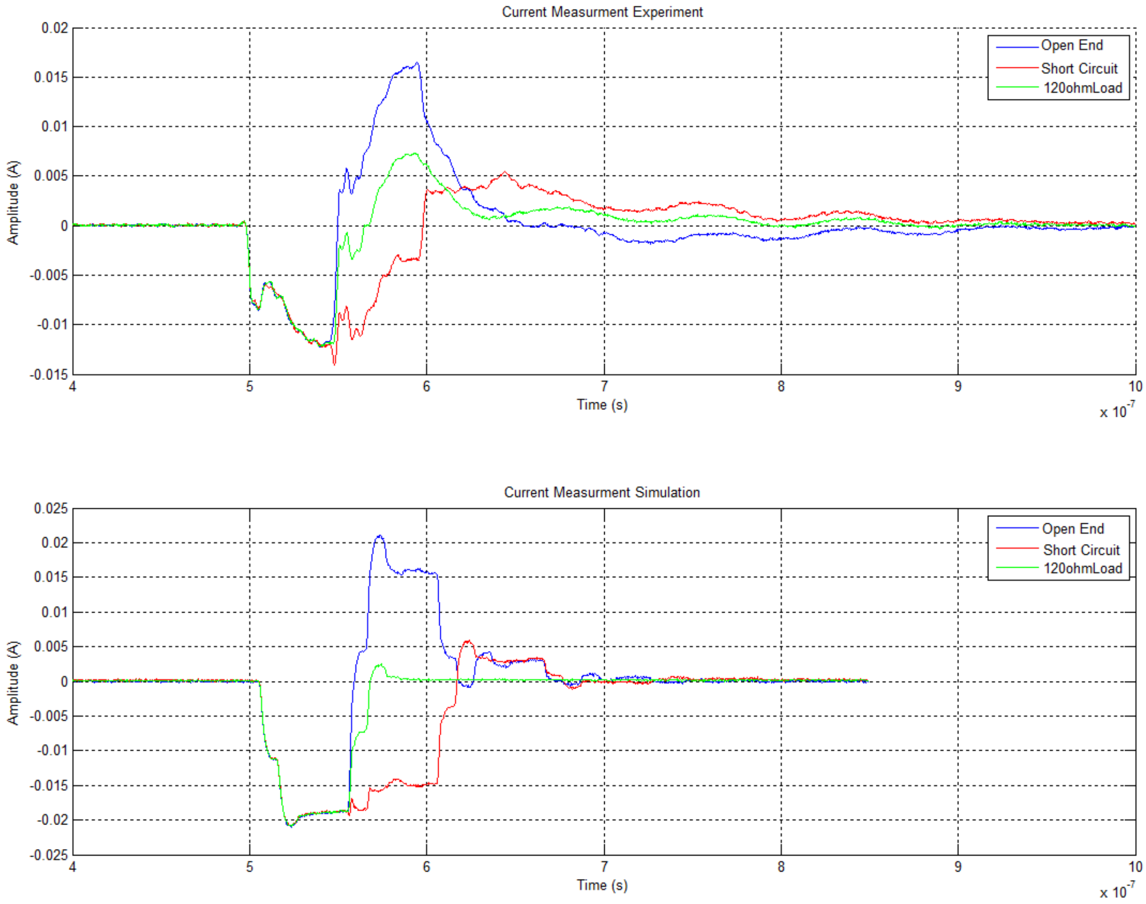

Figure 7-17: Current measurement experiment and simulation

the exact same scenario.

CAN signals for stimulus

Figure 7-18 shows the rise time of a recorded CAN signal. It compares it to the square step signal that was used in the previous experiments as a stimulus. It is noticeable that the rise time for one of this CAN signal is a couple of times slower than the one that was used in the previous experiments, but could in fact be used as a stimulus for TDR. A simulation model using this signal is shown in subsection 7.2.3.

PWM headlights signals for stimulus

Figure 7-19 shows the rise time of a recorded PWM signal from the headlights of a SEAT Leon. In comparison with the rest of the investigated signals, it is easily

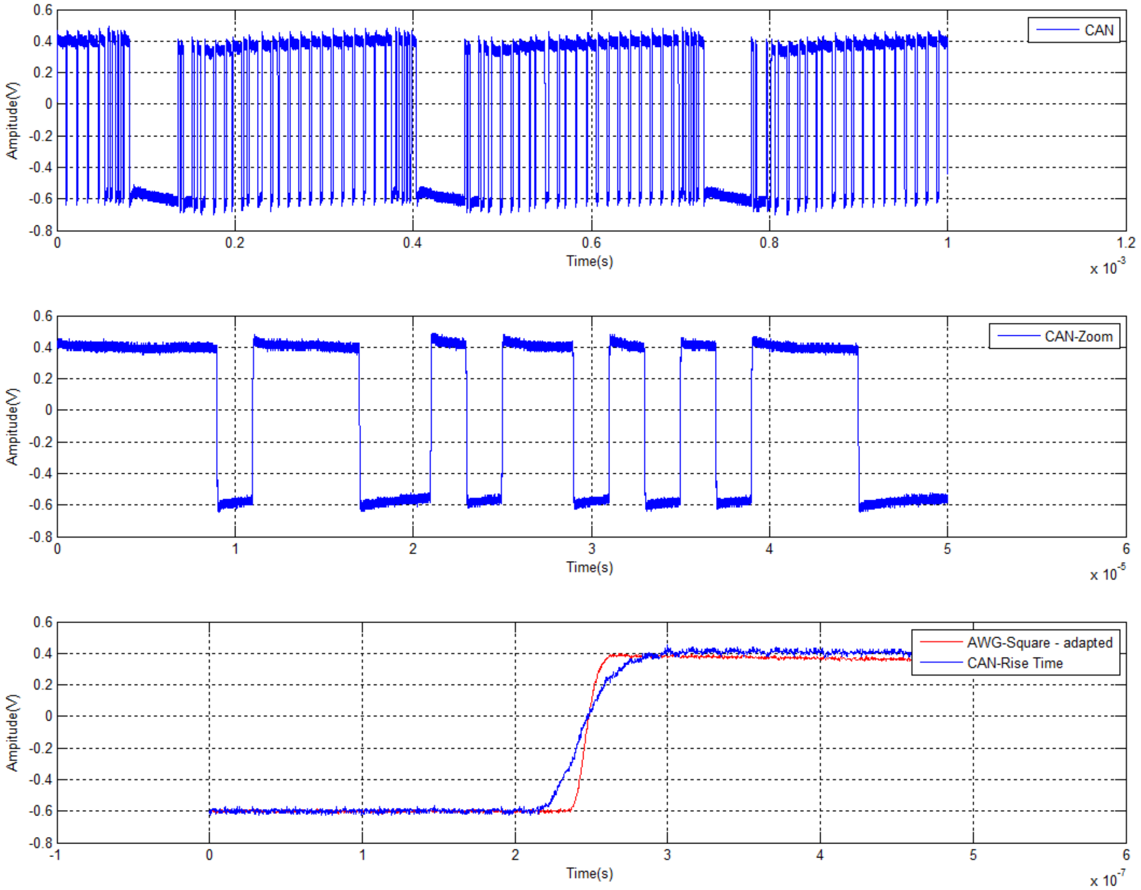

Figure 7-18: CAN signal rise time

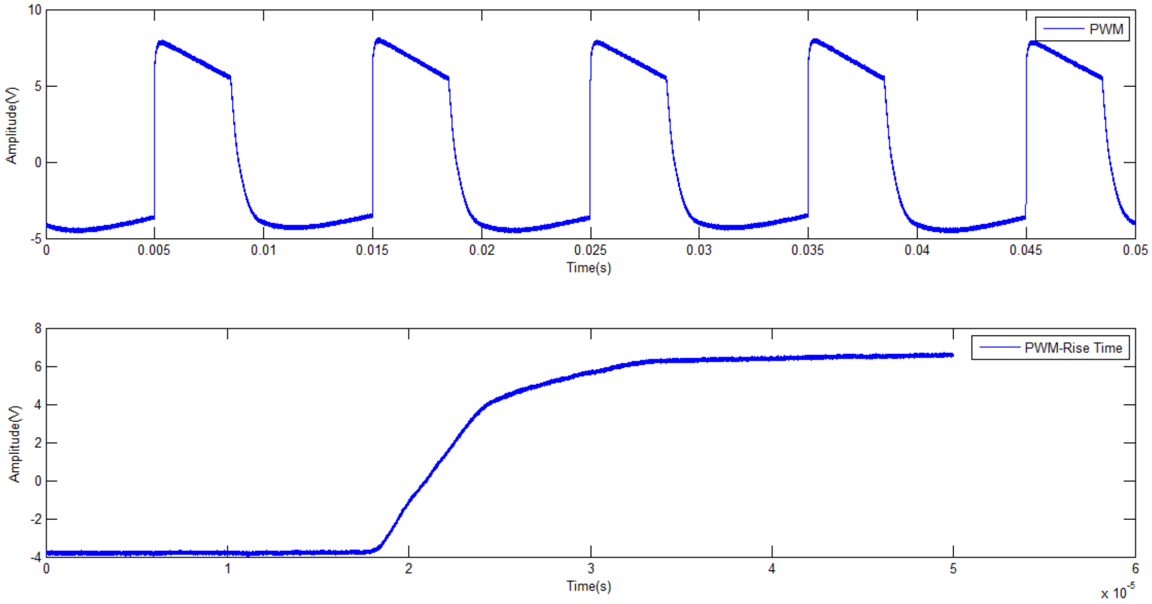

Figure 7-19: PWM from the headlights of a SEAT Leon

noticeable that the rise time for this trace is to slow to be used as a stimulus for TDR.

However as mentioned in section 5.2.5 a Noise Domain Reflectometry (NDR) might be possible with this kind of a signal. More work has to be done in this direction.

Sampling Rates

More measurements were done with different sampling rates in order to estimate the minimum hardware requirements for a cost effective prototype.

With minor changes of the algorithm, through only considering the first four *haar* wavelets, figure 7-20 was obtained for a 100MS/s sampling rate. The first two red peaks, shown in red are the ones of interest as the distance between these two corresponds to the fault location. The green points correspond to the sampled values and one can easily notice that they are in this case 1m apart. Therefore, a fault could be (with such a low sampling rate) only located at multiple of meters. The length of the auxiliary connection cables was of 0.06m. This value is subtracted from the one that is returned from the algorithm in order to get the real length of the cable.

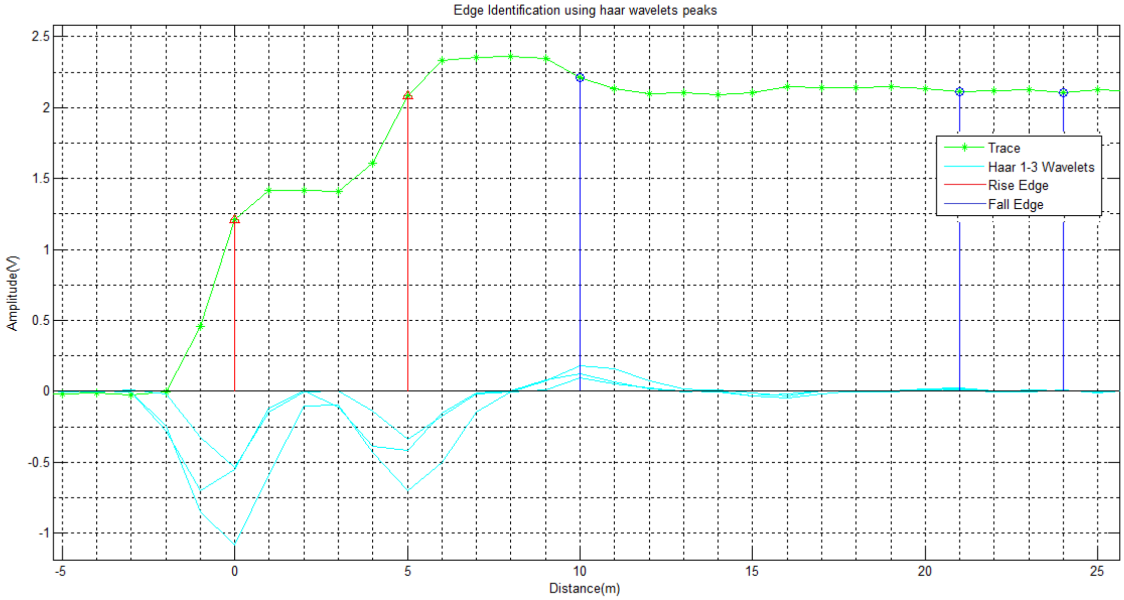

Figure 7-20: Edge detection with haar wavelet on a step with limited rise time on 5m CAN open end wire - 100MS/s

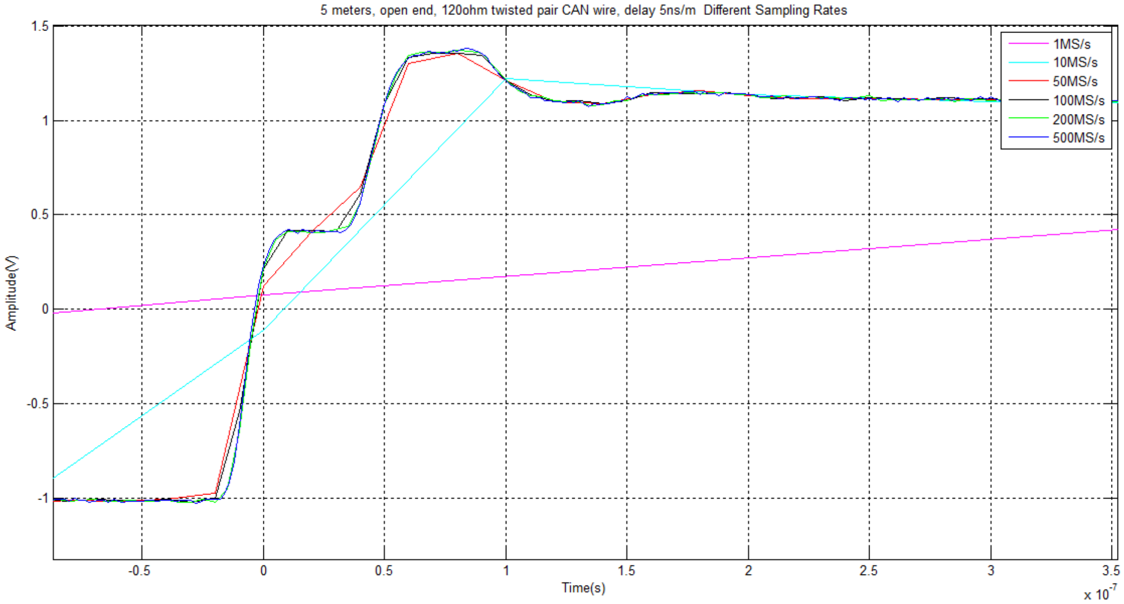

Figure 7-21: Step with limited rise time on 5m CAN open end wire - sampling rates

Table 7.1: Error for figure 7-20

Sampling rate	**Minimum measurable distance between samples(cm)**	**Measured distance (m)**	**Absolute error(cm)**
50MS/s	200	5.88	88
100MS/s	100	4.88	12
200MS/s	50	5.38	38
500MS/s	20	5.08	8

Table 7.1 shows the errors for the modified detection algorithm for the different sampling rates using the *haar* wavelets. The values shown in column 3 can be easily understood when looking at column 2 and when considering that the total measured length was:

$$5m(MeasuredCable) + 0.06m(AuxiliaryCable) = 5.06m \tag{7.1}$$

Therefore in order to measure the length to the fault in the cable, 0.12m(=0.06+0.06)are subtracted from the given algorithm value and the errors in column 3 are explained.

A sampling rate of 100MS/s, shown in green on figure 7-21 shows the reflections on a CAN 5m open end cable with enough accuracy for applying the wavelet algorithm for edge detection that was developed in order to obtain a resolution of 1m.

The algorithm would have to be optimized for the chosen sampling rate and the chosen stimulus signal chosen for each individual application. In a car cable harness, where most of the cables are longer than 50cm long and the topology of the network is known, a 200MS/s sampling rate could be good enough for the location of a fault to a sector of the cable.

7.2 Other Simulation Models

7.2.1 Cable Models

For the cable modelling, two existent transmission line models were used in Orcad Capture and Matlab Simulink. In Simulink, there are four available model types for the transmission line: Delay-based and lossless, Delay based and lossy, Lumped parameter L-section and Lumped parameter pi section. The Parametrization in the last two cases could be done by characteristic impedance and capacitance or by inductance and capacitance.

After analysing all the models and parametrization types, the Matlab Simulink Delay-based and lossy model type was chosen as default model to verify the experiments. For TDR, the PSpice Model was created at first, as seen in figure A-2 in the appendix. After that the Matlab Simulink model was chosen for further investigations and more stimulus signals were used. However, because only two input signals were available for the experimental part, these were recorded and used in the simulations after the model was built.

7.2.2 SSTDR and a new SSTDR with FSK (Frequency Shift Keying)

The idea of this technique is very similar to the traditional SSTDR. However, instead of effectuating a Phase Shift Keying for spreading the spectrum, the Frequency Shift Keying is done as shown in the figure 7-22.

A model for SSDTR was built and an algorithm for automatically measuring the distance to a fault was proposed. This simulation model could be implemented in a prototype that continuously monitors a cable or network. A dynamic baseline is obtained and this is verified for changes.

In the model this is simulated through running the design two times. Once for the cabling without faults and once for the cabling with an impedance change corresponding to a variation to the reference profile.

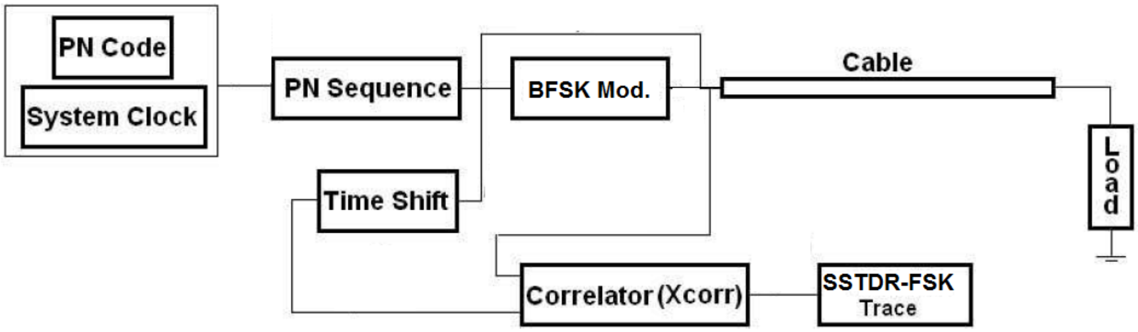

Figure 7-22: SSTDR FSK Diagram

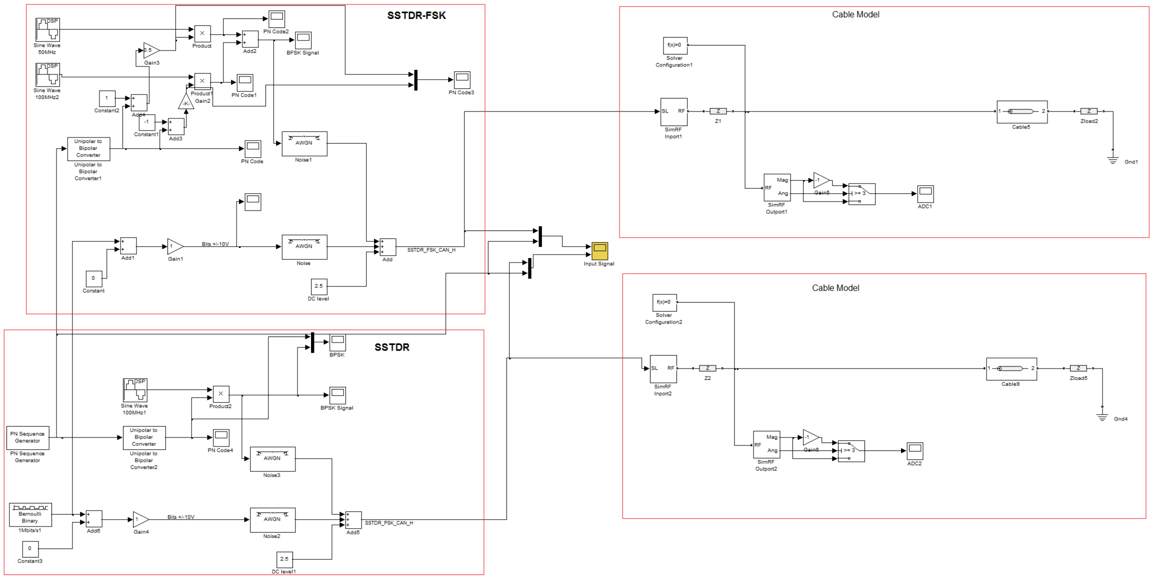

Figure 7-23: Simulink model SSTDR and SSTDR-FSK

More network topologies were simulated and different faults tested out. The algorithm gives a distance from the connection point and could lead to ambiguity in a complex network. The solution to this is offered in [29] where a probability of failure is assigned to each component of the network and thus a better decision could be made when choosing the fault location.

Figure 5-1 shows a block diagram of a Spread Spectrum Time Domain Reflectometry. A model to reproduce such a digram was constructed in Simulink and compared to a new technique in which the frequency is changed in accordance to the PN Code instead of the phase, as seen in 7-23.

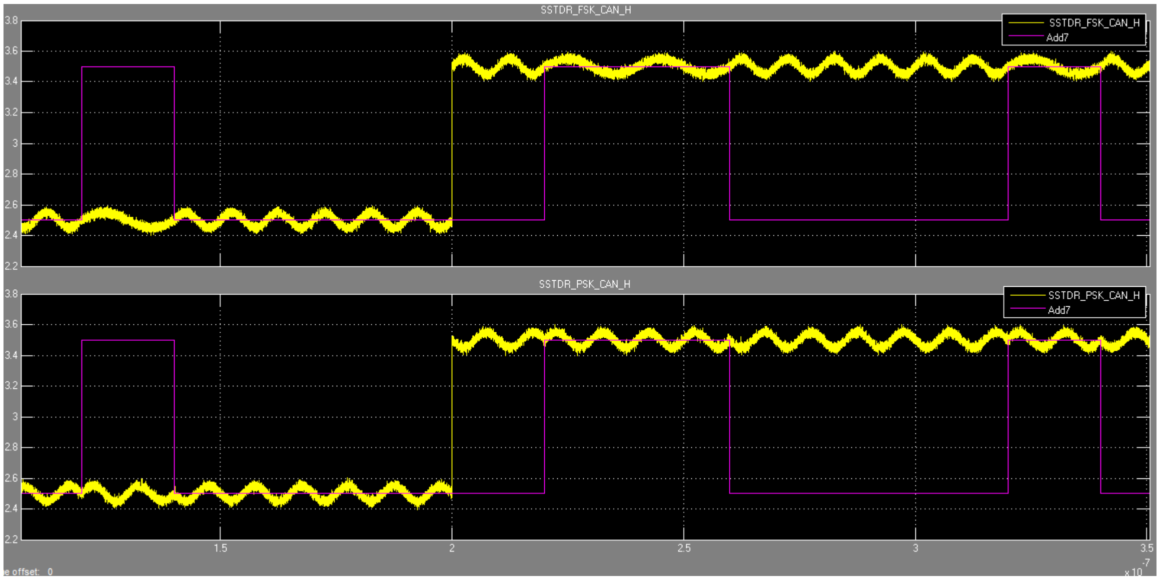

Figure 7-24: SSTDR with BFSK and BPSK input signal

Figure 7-24 shows the over-modulated spread spectrum signal over a square signal, trying to emulate a CAN high message with a possible spread spectrum applied to it. The frequency of the sinusoids are 50MHz and 100MHz.

After inserting this signal in the network and recording the reflections, a cross-correlation of this signal with the original BPSK or BFSK signal with no noise is made. This represents the reference profile. Another simulation where a change is made gives another profile. Through calculation of the squared difference of these two profiles, the location of the impedance change, that is the fault, can be derived:

$$(HealthyProfile - FaultyProfile)^2 = Peaks \tag{7.2}$$

As mentioned in [9], one could obtain a better accuracy when doing the cross-correlation over multiple periods of the PN-Code. Such a calculation can be seen in figure 7-25 for the two SSTDR techniques.

The shape of the cross-correlation and the peaks corresponding to the new FSK technique is apparently noisier. However, considering that in the higher peaks no side lobes are present could make this technique benefit from less signal processing for the accurate detection of the fault.

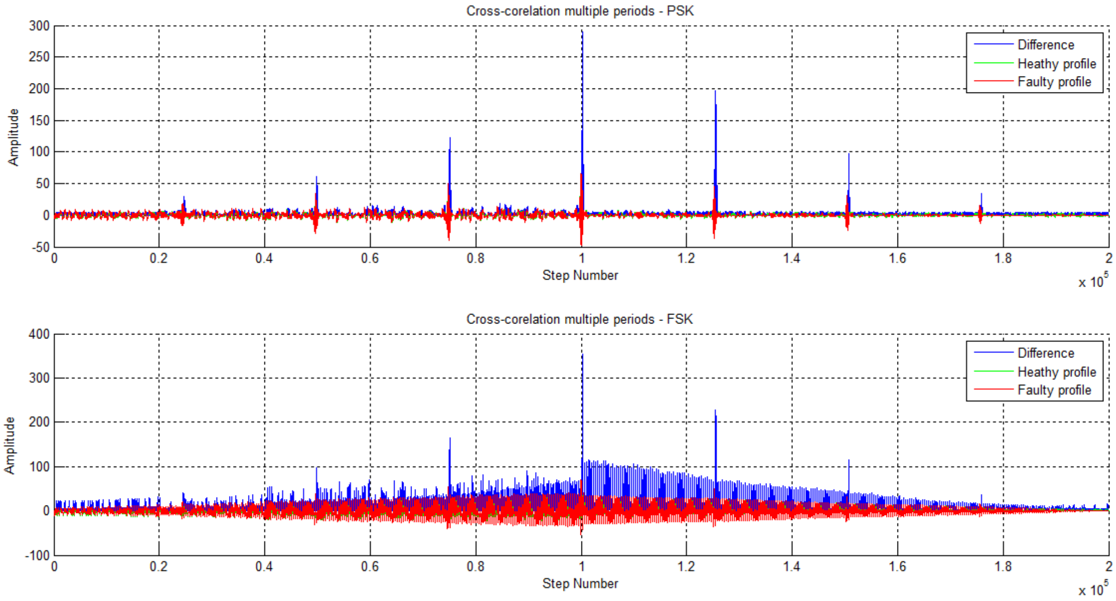

Figure 7-25: Cross-correlation, multiple periods.

The highest peak corresponds to the highest impedance change, that is the location of the fault. Figure 7-26 shows the interesting area of the squared difference from the two cross-correlation profiles. In blue, in the first part of the x-axis, the real location of a fault is shown. The maximum peak for both cases is very close to the real location of a fault. (In this case a 10Ω impedance variation for a 50Ω load situated at the end of a coaxial cable). Worth noticing is that with the frequency shift method, the next highest side-lobe is considerably smaller than in the case of the phase shift, around 50% out of the maximum for FSK and in the case of PSK sometimes higher than 75%. These values were obtained through observations of the simulation values. Different PN Codes and different cross-correlation periods will give different values. Therefore more investigations are recommended in this domain.

An algorithm that only identifies the maximum peaks is desired which would mean a smaller computation time; therefore, the new technique could give better results than the one with phase shift modulation where the peaks next to the location of the fault are sometimes as high if not higher than the one where the fault is. Additionally for the BPSK method a shape detection algorithm should be used to properly identify the correct peak.

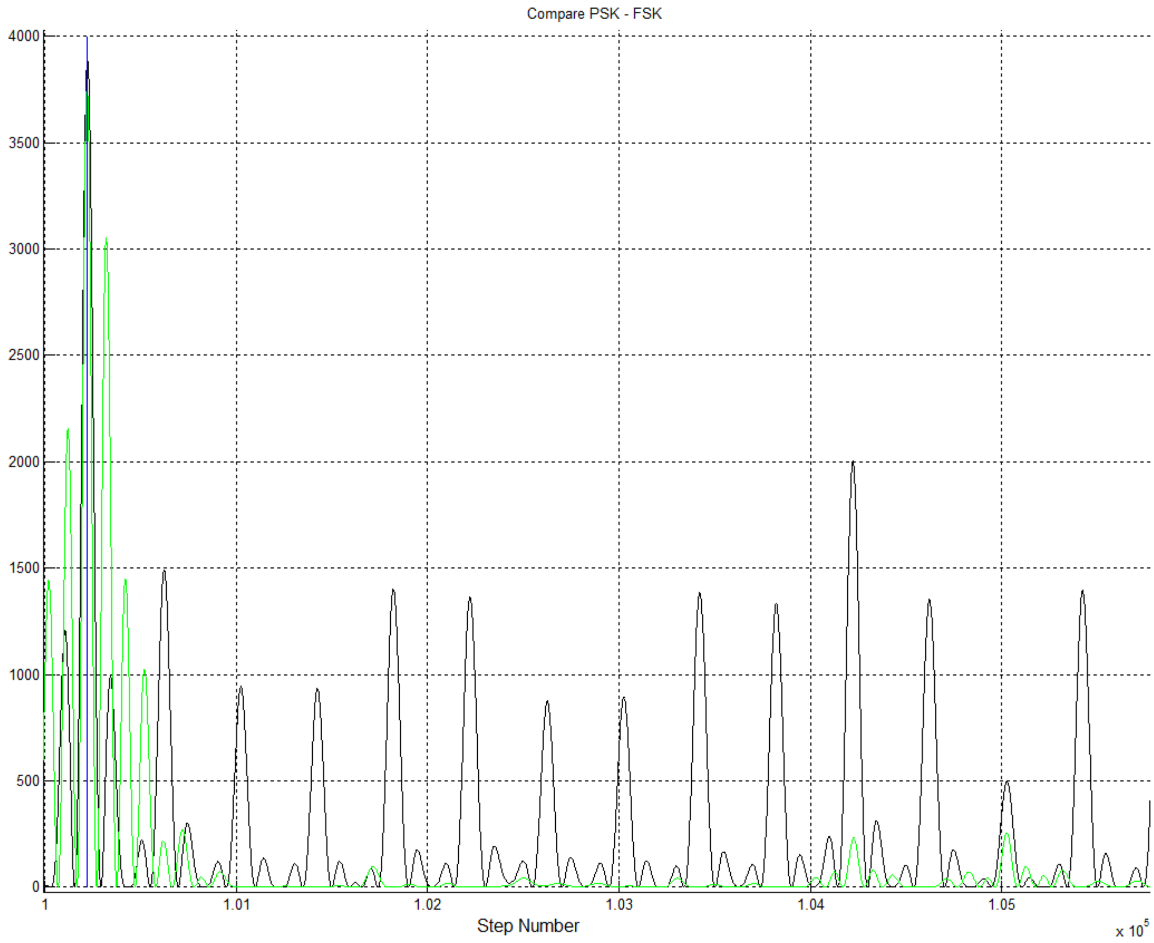

Figure 7-26: Difference comparison. Black-BFSK, Green-BPSK

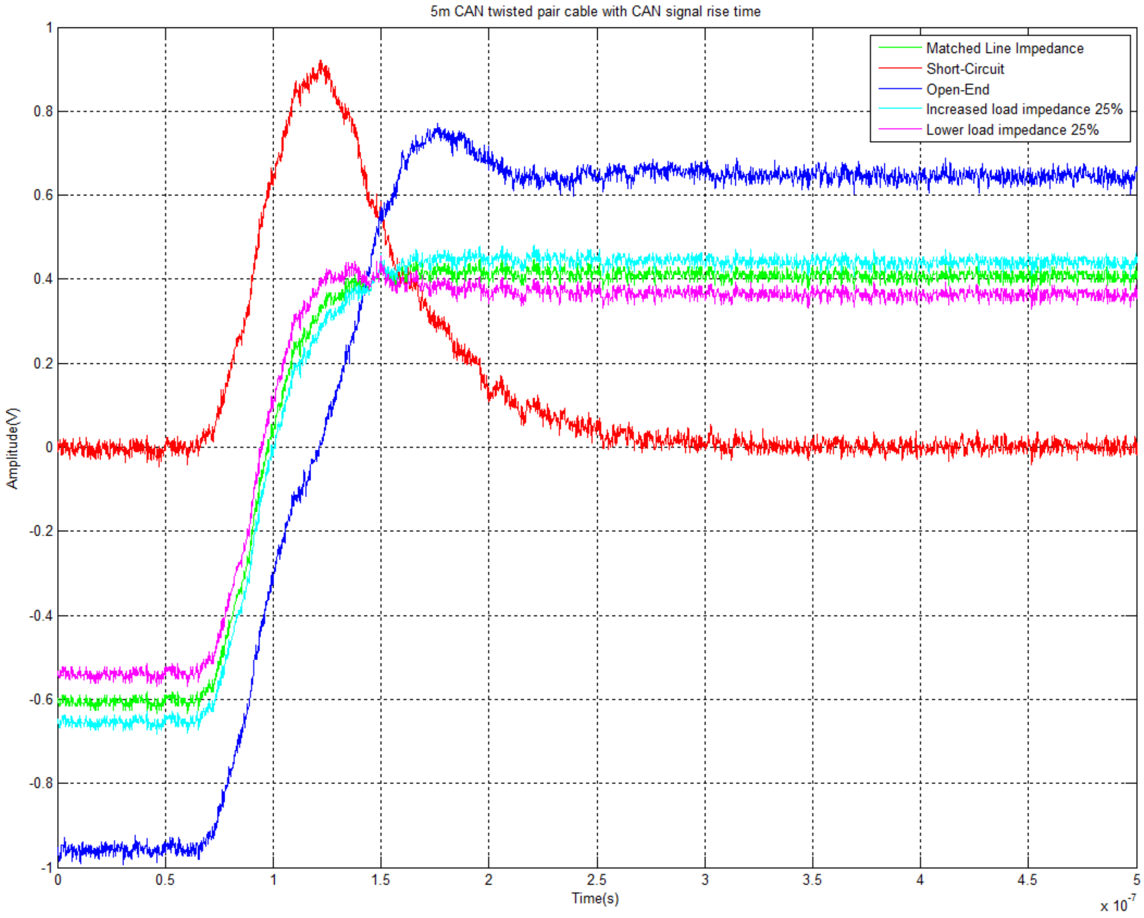

Figure 7-27: A silent CAN signal based TDR

7.2.3 CAN signal-based Reflectometry

A new method of passively monitoring a CAN bus with an ADC is proposed here. Through constantly checking the rise time of the CAN signals, intermittent faults that may occur on the CAN bus could be detected in the physical layer.

A simulation is made for a simple CAN twisted pair wire of a 5 meter length with a load at the end. As stimulus one of the recorded CAN messages is used. The simulated loads are: short-circuit, open circuit, matched impedance (120Ω), increased impedance (150Ω) and smaller impedance (90Ω). Figure 7-27 shows the results of the simulation.

Worth mentioning is that the signals in only one type of transceiver were measured. Other CAN transceivers may have a faster or slower rise time that could lead to an easier or harder detection of the low frequency oscillations in the rise time, corresponding to faults. Implementing such a method for the automotive industry would be challenging as the rise-time of this particular CAN transceiver isn't very fast in comparison to the length of the wires. However in other domains where much longer CAN cables are used such a technique could be very useful.

Chapter 8

Conclusions and Future Developments

This project originally addressed the problem of fault detection on the DC bus of a vehicle, but then it spread on investigating the fault detection and location in the physical layer of a CAN communication bus as well.

A review of the state of the art on reflectometry techniques have been made and many different topics were addressed, such as detecting faults in the cabling, proposing new techniques (SSTDR FSK and CAN based reflectometry) and possible uses in the automotive industry (grounding cable validation).

There have been different personal contributions to this project: a new Sread Spectrum Time Domain Reflectmetry technique and another CAN signal-based reflectometry technique were proposed, a signal processing algorithm based on wavelets was developed, the detection of faulty mass connections through TDR was investigated and a high correlation between the simulation and experimental results for TDR on coaxial 50Ω impedance cables and 120Ω twisted pair cables was obtained.

The work comes more as a study on fault detection and uses in the automotive industry. Now that the possible application were stated, one needs to focus on one topic at a time and build a prototype for solving the punctual problems. Than the prototype could be adapted for multiple uses in the automotive sector and the quality and reliability of the cable harness could be drastically improved.

8.1 Conclusions

- Developed a simulation model for TDR for coaxial 50Ω line impedance and CAN twisted pair 120Ω line impedance cables that was experimentally validated and can be used for future work and for developing digital signal processing algorithms.

- TDR could be a cost effective solution for fault detection and location in the wiring of a vehicle when compared to the commercial ones. Even more when only the detection is desired and the location of the faults is not important.

- A big advantage of implementing TDR in the automotive sector, is that custom signal processing for the exact car problem, for example grounding cables correct instalment, could be developed and better results than a commercial off the shelf fault detection product could be obtained.

- Some reflectometry techniques (for example SSTDR) offer the possibility of online detection. That means detecting intermittent faults before they create real damage could be a reality in the car industry.

- Open connector, short circuits, faulty masses and increased impedances can be easily detectable with simple TDR measurements. Experiments have shown that the accurate location up to a hard fault can be obtained through a wavelet edge detection algorithm.

8.2 Future Developments

- The accuracy of TDR depends on the rise time of the pulse and the sampling rate of the receiver. [32] However, more investigations have to be made when only the detection is desired and the localization or accuracy is not that important. This could lead to the introduction of very cheap fault detectors.

- The problem of detection soft faults is still very challenging. Even though new reflectometry techniques such as the Joint Time Frequency Domain Reflectometry (JTFDR) are showing promising results in the lab environment, an industrial application is not yet available as this technique is not fully developed.

- As these new techniques are showing that small impedance changes could be detected, the question arises if temperature could be measured in the cabling through the use of reflectometry techniques. Knowing the worst case scenario temperature in every conductor of a vehicle would give the possibility of optimising the cable harness and possibly lowering the overall weight of the vehicle. No research has been yet done on this topic.

- More experiments have to be done with SSTDR and the idea of spreading the spectrum through frequency shift keying instead of phase shift keying has to be tested. The spectrum is spread in time domain according to a PN Code. In [31] it is stated that ML codes were identified as the best codes to use for testing single wires. The optimum code for branched networks and for networks with short wires such as the ones in the cars has to be identified.

- A cost effective embedded ECU for the safety related critical systems (ABS, ESP, airbags, servo-steering, etc.) should be built and thoroughly tested.

- Development of a hand-held device for confirming the correct installation of grounding cables and for other cables in general. Such a device would improve the quality of the cabling in new vehicles. A device like this could be used for all the vehicles without the need of being embedded. The cost of the device itself would therefore not be problematic.

- These techniques could also be applied in detecting the faults in electric motors and power converters. [27] Some papers have shown that this is possible. Embedding a fault detection reflectometry circuit in the power-train of electric and hybrid vehicles should therefore be considered.

- More experiments and studies should be made with square signals similar to a PWM (the PWM from the LED headlights of a SEAT Leon, the square-shaped signal and the CAN bus signals). This topic is important as this shape of the signals is very common in converters and electric motors and could be used for a continuous monitoring of the cabling that connects the motor to the converter or of the control wiring.

- The excitation signal used in some experiments was compared with the CAN signals measured in a vehicle to assess the feasibility of implementing a CAN signal based reflectometry technique for the CAN bus. Experiments on live CAN buses have to show that locating faults in the physical layer is indeed achievable. More work on embedding such a device on the communication buses of vehicles has to be done.

Appendix A

Figures

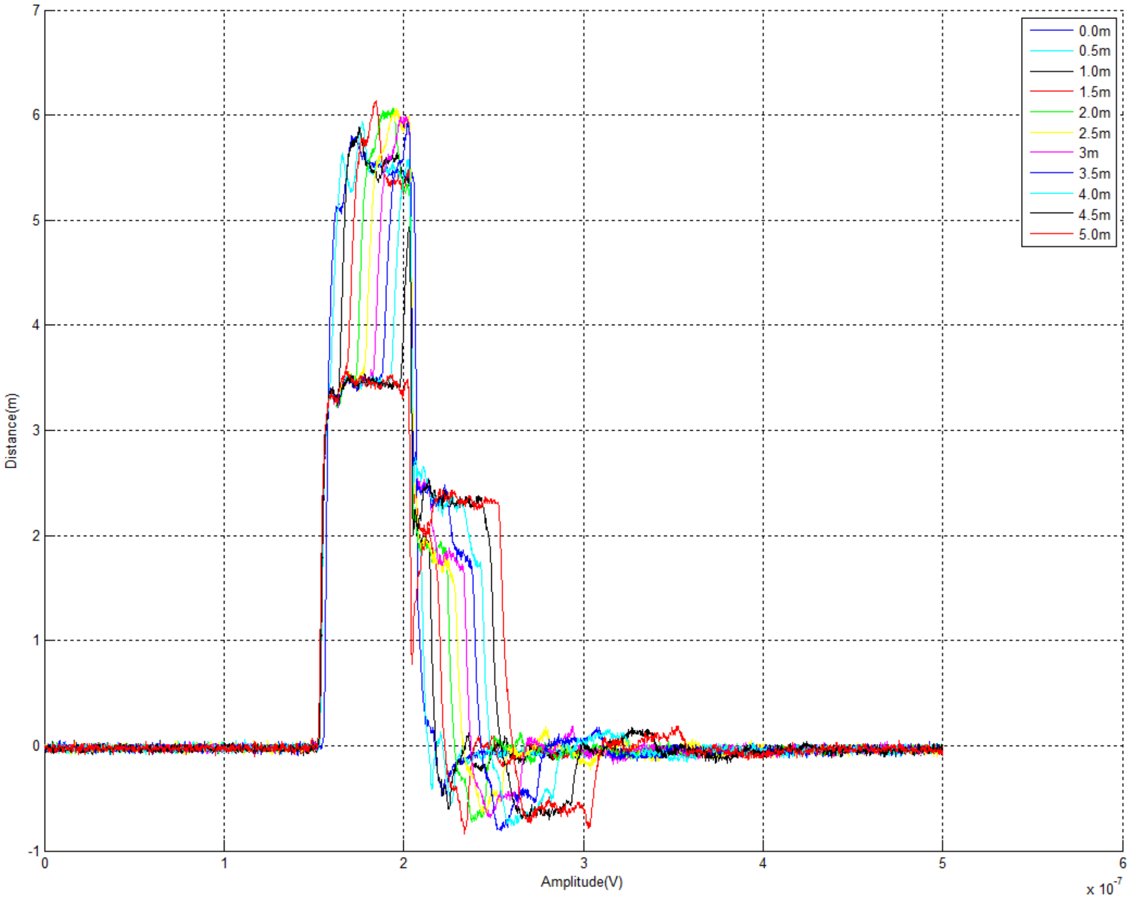

Figure A-1: TDR Experiment for a CAN twisted cable of different lengths

50ns pulse, in a 120ohm impedance cable: open end

50ns pulse, in a 120ohm impedance cable: matched impedance

50ns pulse in a 120ohm impedance cable: short-circuit

Figure A-2: PSpice TDR simulation with a 50ns pulse in a 120Ω impedance wire of 1m

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