A low Cost Time Domain Reflectometry Circuit for printed Electronic Applications

KONSTANTIN VARDANYAN

Master of Science Thesis
Stockholm, Sweden 2013
TRITA-ICT-EX-2013:235
FINAL REPORT

A Low Cost Time Domain Reflectometry Circuit for Printed Electronic Applications.

Student name: Konstantin Vardanyan

Data: 2013.05.30
Acknowledgement

First and foremost I would like to show my appreciation to my supervisor Dr. Fredrik Jonsson. There are no words in order to express the admiration and respect to him. I am really proud that I was a student of him.

I want to thank to Jue Shen, who help me a lot during the project. She is a senior Ph.D student of great knowledge and expertise. She is very kind and very responsible person and was ready to solve any problems occurred during project.

I am also grateful to my family for their constant support, which has been fundamental during this time.

My very special thank is to my wife and my little handsome son. They were with me during all this time physically and mentally and without them this project would never be finished.
# INDEX

## 1. INTRODUCTION

- 1.1 PROJECT DESCRIPTION .................................................................................. 4
- 1.2 TDR APPLICATIONS ..................................................................................... 4
- 1.3 TDR PRINTED ELECTRONICS APPLICATIONS ............................................. 6
- 1.4 PROJECT CONCEPT ...................................................................................... 8

## 2. THEORY

- 2.1 INTRODUCTION.............................................................................................. 10
- 2.2 TRANSMISSION LINE STRUCTURES .......................................................... 10
- 2.3 WAVE PROPAGATION .................................................................................. 11
- 2.4 PARAMETERS OF TRANSMISSION LINE .................................................. 12
- 2.5 CHARACTERISTIC IMPEDANCE TRANSMISSION LINE .............................. 14
- 2.6 PROPAGATION VELOCITY, TIME AND DISTANCE ...................................... 16
- 2.7 INITIAL WAVE ............................................................................................ 17
- 2.8 RISE TIME EFFECT ON REFLECTIONS .................................................... 20

## 3. PRACTICAL PART

- 3.1 TIME DOMAIN REFLECTOMETER ............................................................... 22
- 3.2 TIME DOMAIN REFLECTOMETER TESTING .............................................. 24
- 3.3 LOCATING MISMATCHES ............................................................................. 25
- 3.4 ESTIMATING REFLECTIONS ....................................................................... 26
- 3.5 LINE WITH DISCONTINUITIES .................................................................... 28
- 3.6 RECKONING UP CABLE LOSS ..................................................................... 29
- 3.7 MULTIPLE DISCONTINUITIES ..................................................................... 32
4. RESULTS AND DISCUSSIONS .................................................................................. 34

4.1 MAIN CIRCUIT ................................................................................................. 34
4.2 SIMULATIONS ................................................................................................... 37
4.3 DFF DESIGN ..................................................................................................... 40
4.4 START-UP CIRCUIT DESIGN ........................................................................... 45
4.5 FREQUENCY SIMULATIONS .............................................................................. 49

5. CONCLUSION ........................................................................................................ 51

5.1 CONCLUSION .................................................................................................... 51
5.2 FUTURE PLANS ............................................................................................... 51
5.3 REFERENCES .................................................................................................... 52
CHAPTER 1. INTRODUCTION

1.1 Project Description

The Time Domain Reflectometer (TDR) is a method with the help of which a short duration of pulse with a very fast rise time is sent into an electrical line in order to solve signal integrity issues. The main idea of TDR is reflected waveform from the sent pulse which can be used to calculate the characteristics of the line. Time Domain Reflectometer circuits can have different impedance mismatches: open, short, or any others. In this project the impedance mismatch is short circuit, which means that the signal sent into transmission line is reflected back totally.

1.2 TDR Applications

There are a lot of possible applications where TDR method could be used. For instance TDR radars, this combination of technologies to the level market a high speed radar circuit, which is speed of light.

![Figure 1.2.1 TDR guided wave radar level transmitter](image-url)
This type of transmitters can be used not only for radars but for many other applications.

The Time Domain Reflectometers are also used in telecommunication industry. As mentioned above the main idea of the TDR instruments from the beginning is cable tester. Hence in telecommunication industry TDR instruments are used to identify locations of discontinuities in cables. TDR technology allows the operator to determine locations of line breaks or other damage to cables using travel time analysis.

Using similar principles, a waveguide or probe of known length L may be embedded in soil (Figure 1.2.2) and the travel time for a TDR-generated electromagnetic ramp to traverse the probe length may be determined. From the travel time analysis the soil’s bulk dielectric constant is computed (the terms dielectric constant and dielectric permittivity are synonymous), from which the volumetric water content is inferred.

Figure 1.2.2 TDR cable tester with three-rod probe embedded vertically in surface soil layer
1.3 TDR Printed Electronics Applications

As the circuit design in this project is for use in printed electronic techniques, so here are some TDR printed electronics applications. On the figure 1.3.1 is stated an example of printed transmission line on the paper.

![Printed Transmission Line](image)

**Figure 1.3.1 Printed Transmission Line**

One way of using printed transmission line technology is the ink-jet print code; with the help of this application it is possible to read a code. The way it works is illustrated on figure 1.3.2.

![Ink-jet print code technique](image)

**Figure 1.3.2 Ink-jet print code technique**

As can be seen from the figure with the help of pushing the bottoms we make short circuit. As the numbers (codes) are stated continuously, so there will be change in frequency of signal traveling through the transmission line and that change is different for different number. The change of frequency is due to the change of the length of transmission line. To sum up, in case of pushing different numbers the circuit will measure different frequencies and it will read a code.
The printed TDR circuits can be used also in medical applications; one of the examples is package for the pills. See figure 1.3.3.

The way this technique works is same as the ink-jet print code. Here in case of code we have pills. Here with the help of printed transmission line it is possible to count the pills in the package, as every time when a pill will be taken out from the package there will be change in transmission line and that will influence on frequency of the signal. On the figure 1.3.4 is illustrated the way how it works:

Other application can be the paper keyboard. The structure is same as in ink-jet print code technique. Here also we have transmission line printed on a paper and instead of code we read letters.
1.4 Project Concept

A Time Domain Reflectometer was designed by me with the given task. The whole circuit structure by block level is illustrated on figure 1.2.1.

As we can see the Time Domain Reflectometer which I design includes 4 main blocks. First block is Pulse Generator, where we generate the first pulse which after will travel through the transmission line. The generated first pulse is 1.2V.

The upcoming second part is the transmission line block. The signal generated by pulse generator will travel through the transmission line it will be reflected back totally
as in the end of the transmission we have short circuit by connecting the edge to the ground.

The next block is pulse extension block. The main idea of having this part is to catch the signal which is reflected back from the end of the transmission line and also to generate the pulse with the fixed length. That means independently from the input pulse length (signal coming from transmission line) it has to generate a pulse with the fixed length. I reach to that with the help of edge sensitive DFF which generates a pulse only when it sees the rising edge of the input pulse.

The fourth one is the delay block. The use of the delay block is for generating very short pulse.

The fifth and final block is the start up circuit which is for generating first pulse for the circuit. As we know the full circuit has to oscillate itself but anyway we have to generate the first pulse and then it will start to oscillate itself.
CHAPTER 2. THEORY

2.1 Introduction

Nowadays as we have high-speed digital systems, consequently, it is obvious that engineers have to treat the printed circuit board (PCB) traces as transmission lines. As the timing issues associated with the transmission lines on total timing margin are becoming a significant percentage, so it is no longer possible to design interconnects as lumped capacitors or usual delay lines, which could be done on low speed designs. In order to have controlled electrical characteristics of the transmission lines, we have to pay a lot of attention to the construction of the PCB. The following chapter introduces the basic transmission line theory for the ideal cases, basically used in digital systems.

2.2 Transmission line structures

Mainly, the transmission line structures that can be seen on PCB or multichip module (MCM) consist of conductive traces and those are buried or attached to insulating or dielectric material. On the PCB we usually have copper and dielectric is FR4, the FR4 is a type of fiberglass.

For digital design there are two common cases of the transmission lines, those are: microstrips and striplines. A microstrip (figure 2.2.1 (a)) transmission lines have only one reference plane and they are routed on the outside layer of PCB. But the stripline (figure 2.2.1 (b)) transmission lines are routed on the inside layer of PCB, hence it has two reference planes. On the figure 2.2.1 (a), (b) we have PCB traces routed between the various components on both internal (stripline) and external (microstrip) layers.
As can be seen from picture there is a cross section, the idea is to see the position of transmission lines relative to the ground/power planes. The structure that we have on figure 2.2.1 may provide a mixture of both structures (microstrip and stripline). As mentioned above the control of the electrical characteristics of the transmission line in high-speed systems is one of the most challenging parts during the circuits design and these electrical characteristics are defined as transmission line parameters.

2.3 Wave Propagation

The important thing to know is, that during high frequencies the digital signal will be influenced by the transmission line effects, if the rise and fall time of that signal are smaller than the propagation delay of the electrical signal which is travelling down the PCB trace. In order to explain more clearly wave propagation let’s take water in long square pipe as an example structure. So, the electrical signal will travel down the transmission line in the way that water trough a long square pipe. Hence, this is called electrical wave propagation. Furthermore, the waterfront will travel as a wave down the pipe, so an electrical signal will travel as a wave down a transmission line. Moreover, just as water needs finite amount of time, in order to travel the length of the pipe, consequently, the electrical signal will travel the length of the transmission line in a finite amount of time. In addition, the height of the water inside the pipe can be compared to the voltage in transmission line and also the water flow can be compared.

Figure 2.2.1 Transmission lines in a typical design built on a PCB
to the current in transmission line. On figure 2.3.1 illustrates the common way of a transmission line.

![Figure 2.3.1 Digital signal propagating in transmission line](image)

From the picture showed above we can see that the top line is the signal path and the bottom line is the current return path. From the point “A” onto the line the $V_i$ initial voltage is lunched.

### 2.4 Parameters of Transmission Line

In order to analyze the influences that transmission lines have on system at first the electrical characteristics should be modified. The most important electrical characteristics are mainly the characteristic impedance and the propagation velocity of the transmission line. The width of water in above mentioned example is similar to the characteristic impedance and the speed of water in pipe is similar to propagation velocity. The important thing is to derive these terms, so it is indispensable to look at the main properties of a transmission line.

On figure 2.3.1 we have signal which travels through the signal path and the current return path, so there will be a voltage differential between those two paths. So when the signal reaches an arbitrary $z$ on transmission line, hence the signal path conductor will be at potential of $V_i$ (Volts), this means that the ground return conductor will be at a potential of 0 (Volts). As we have voltage difference, consequently, there is an electric field between the signal and ground return conductors. As we know from Ampère's law “the line integral of the magnetic field taken about any given closed path must be equal to the current enclosed by that path”, to be more clear this means that if there is a current flow through the conductor, so it will result in a magnetic field around
the conductor. But for our case as the output buffer injects a signal of voltage \( V_i \) and current \( I_i \), onto a transmission line, respectively it will persuade an electric and magnetic field. Nevertheless, voltage \( V_i \) and current \( I_i \) will be zero at any arbitrary point on the z line, until the time \( z/v \), where \( z \) is the distance from the source and \( v \) is the velocity of the signal travelling down the transmission line.

Now when the basic electromagnetic properties of transmission line are modified, it is possible to design a simple circuit model for small section of the line, the circuit model is shown on figure 2.4.1.

On the figure 2.4.1 we can see the cross section of the microstrip transmission line and the arrows represent the electric and magnetic field respectively. If we assume that there are no components of the electric or magnetic fields propagating in the z direction (into the page), in that case the electric and magnetic fields will be orthogonal. This is called transverse electro-magnetic mode (TEM).

Transmission lines will propagate in TEM mode under normal circumstances and it is an adequate approximation even at relatively high frequencies. This allows us to examine the transmission line in differential sections (or slices) along the length of the line traveling in the z-direction (into the page). The two components shown in figure 4.2.1 are the electric and magnetic fields for an infinitesimal or differential section (slice) of the transmission line of length \( dz \).

![Figure 2.4.1 Cross section of a microstrip depicting the electric and magnetic fields assuming that an electrical signal is propagating down the line into the page.][1]

Since there is energy stored in both an electric and a magnetic field, let us include the circuit components associated with this energy storage in our circuit model. The
magnetic field for a differential section of the transmission line can be represented by a series inductance $L dz$, where $L$ is inductance per length. The electric field between the signal path and the ground path for a length of $dz$ can be represented by a shunt capacitor $C dz$, where $C$ is capacitance per length. An ideal model would consist of an infinite number of these small sections cascaded in series. This model adequately describes a section of a loss-free transmission line (i.e., a transmission line with no resistive losses).

In any case as in PCB metals are not infinitely conductive and also the dielectrics are not infinitely resistive, so we have to add to the model lost mechanisms and that will be in the form of a series resistor, $R dz$, and a shunt resistor to ground referred to as a conductance, $G dz$, with units of siemens (1/ohm).

![Equivalent circuit model of a differential section of a transmission line of length dz (RLCG model).](image)

Figure 4.2.2 Equivalent circuit model of a differential section of a transmission line of length dz (RLCG model).

Figure 2.4.2 depicts the equivalent circuit model for a differential section of a transmission line. The series resistor, $R dz$, represents the losses due to the finite conductivity of the conductor; the shunt resistor, $G dz$, represents the losses due to the finite resistance of the dielectric separating the conductor and the ground plane, the series inductor, $L dz$, represents the magnetic field; and the capacitor, $C dz$, represents the electric field between the conductor and the ground plane.

### 2.5 Characteristic Impedance Transmission Line

The ratio of voltage and current waves at any point of the transmission line modifies the characteristic impedance of the transmission line ($Z_0$); hence $Z_0 = V/I$. On figures 2.5.1 and 2.5.2 we can see the representations of transmission line. Figure 2.5.1 states the differential section of transmission line of length $dz$ constructed with RLCG element. For this case the characteristic impedance of the RLCG element is defined as
the ratio of the voltage $V$ and current $I$. If we assume that the load $Z_0$ is exactly proportional to characteristic impedance of the RLCG element, therefore the figure 2.5.1 can be represented by figure 2.5.2, for this case we have infinitely long transmission line.

As can be seen from figure 2.5.1 it represents the infinite number of additional RLCG segments of impedance $Z_0$ that include the entire transmission line model.

As long as the voltage/current ratio ($Z_0$) is same as that in the RLCG segment, then from voltage source view figure 2.5.1 and 2.5.2 will be indiscernible.

In order to derive the equation for characteristic impedance of transmission line, we have to examine figure 5.2.1. Solving the equivalent circuit of figure 2.5.1 for the input impedance with the assumption that the characteristic impedance of the line is equal to the terminating impedance, $Z_0$, yields equation (2.1). For simplicity, the differential length $dz$ is replaced with a short length of $\Delta z$.

The derivation is as follows: Let

\[
\begin{align*}
    jwL(\Delta z) + R(\Delta z) &= Z\Delta z \quad \text{(series impedance for length of line $\Delta z$)} \\
    jwC(\Delta z) + G(\Delta z) &= Y\Delta z \quad \text{(parallel admittance for length of line $\Delta z$)}
\end{align*}
\]

Then:
Assuming that the load is equal the characteristic impedance,

\[ Z(\text{input}) = Z_0 = \frac{(Z_0 + Z\Delta z)(1/Y\Delta z)}{Z_0 + Z\Delta z + 1/Y\Delta z} \]

Where \( R \) is in ohms per unit length, \( L \) is in Henries per unit length, \( G \) is in Siemens per unit length, \( C \) is in Farads per unit length, and \( w \) is in radians per second. But is usually common to write \( Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \) (2.1), because both \( R \) and \( G \) tend to be significantly smaller than the other terms. Nevertheless at very high frequencies or with very lossy lines the \( R \) and \( G \) components become significant.

Thus,

\[ Z_0 = \frac{Z}{Y} = \frac{R + j\omega L}{\sqrt{G + j\omega C}} \]

(2.2)

Where \( R \) is in ohms per unit length, \( L \) is in Henries per unit length, \( G \) is in Siemens per unit length, \( C \) is in Farads per unit length, and \( w \) is in radians per second. But is usually common to write \( Z_0 = \sqrt{L/C} \), because both \( R \) and \( G \) tend to be significantly smaller than the other terms. Nevertheless at very high frequencies or with very lossy lines the \( R \) and \( G \) components become significant.

### 2.6 Propagation Velocity, Time and Distance

In transmission line electrical signal will travel with speed which depends on surrounding. So the propagation delay is measured be seconds per meter, hence it is inverse of propagation velocity. The propagation delay will increase in proportion to the square root of the surrounding dielectric constant. It needs to be mentioned that the time delay of transmission line is simply the amount of time it takes for a signal to propagate the entire length of the line. The relationships between the dielectric constant, the propagation velocity, the propagation delay, and the time delay are stated below:

\[ V = \frac{c}{\sqrt{\varepsilon_r}} \]  (2.2)
\[ PD = \frac{1}{v} \quad (2.3) \]
\[ TD = \frac{x\sqrt{\varepsilon_r}}{c} \quad (2.4) \]

Where,
\[ v = \text{propagation velocity, in meters/second} \]
\[ c = \text{speed of light in a vacuum (3 \times 10^8) m/s} \]
\[ \varepsilon_r = \text{dielectric constant} \]
\[ PD = \text{propagation delay, in seconds per meter} \]
\[ TD = \text{time delay for a signal, in order to propagate down a transmission line of length } x \]
\[ x = \text{length of the transmission line, in meters} \]

The time delay can be calculated also from the equivalent circuit model of transmission line:
\[ TD = \sqrt{LC} \quad (2.5) \]

Where \( L \) is the total series inductance for the length of the line and \( C \) is the total shunt capacitance for the length of the line.

In equation (2.2) through (2.4) assume that no magnetic materials are present, such that \( \mu_r = 1 \), hence the magnetic materials can be left out from the formulas.

2.7 Initial Wave

The integrity of a signal being transmitted from one device to another is affected by the characteristics of the driving circuitry and of course transmission line. Consequently, it is very important to figure out how the circuits should be design, how the signal should be launched and how it will look at the reciver. Anyway some of the parameters will affect the integrity of the signal at the reciver, in below sections we will explain most basic behavior.

Furthermore, when we have signal launched onto a transmission line by driver, the magnitude of the signal depends on the voltage and source resistance of the buffer and of course the impedance of the transmission line. Moreover, the initial voltage at the
driver will be controled by the voltage divider of the source resistance and the line impedance. On figure 2.7.1 illustrated an initial wave being launched onto a transmission line.

![Figure 2.7.1 launching a wave onto a long transmission line](image)

As can be seen from figure 2.7.1 an initial wave being launched onto a long transmission line. So the voltage $V_i$ will propagate down the transmission line until it will reach to the end. And the magnitude of $V_i$ will be modified by the voltage divider between the source and the line impedance:

$$V_i = V_S \frac{Z_0}{Z_0 + Z_S} \quad (2.6)$$

So, if the end of transmission line is concluded with an impedance which has exactly same value with characteristic impedance of transmission line, than the signal with amplitude $V_i$ will be terminated to ground and the voltage $V_i$ will stay on the line until the signal source switches again. In this case the voltage $V_i$ is the dc steady-state value. But in case when we have the end of transmission line concluded with some impedance which doesn’t have same value with characteristic impedance of transmission line, than a portion of the signal will be terminated to ground and remainder of the signal will be reflected back down the transmission line to the source. Consequently, the portion of the signal reflected back is modified by the reflection coefficient, defined as the ratio of the reflected voltage to the incident voltage seen at a given junction. In here junction means an impedance discontinuity on a transmission line. Of course the transmission line cannot have same characteristic impedance, so the impedance discontinuity could be a section of transmission line with different
characteristic impedance, a terminating resistor, or the input impedance to a buffer on a chip. Hence the reflection coefficient is calculated as follows:

\[ \rho = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_t - Z_0}{Z_t + Z_0} \tag{2.7} \]

Impedance of the line, and \( Z_t \) the impedance of the discontinuity. The equation assumes that the signal is traveling on a transmission line with characteristic impedance \( Z_o \) and encounters an impedance discontinuity of \( Z_t \). Note that if \( Z_o = Z_t \), the reflection coefficient is zero, meaning that there is no reflection. The case where \( Z_o = Z_t \) is known as matched termination.

On figure 2.7.2 we can see easily that when the incident wave hits the termination \( Z_t \), so a portion of signal (\( V_{\text{ip}} \)) is reflected back toward the source and it is obvious that reflected signal should be added to the incident wave in order to produce a total magnitude on the line of \( V_{\text{ip}} + V_i \). But the reflected back component will then travel to the source and maybe generate another reflection on the source. These reflections will continue until the line will reach a stable condition.

![Figure 2.7.2 Incident signal being reflected from an unmatched load](image)

Figure 2.7.3 (a,b,c) illustrates special cases of the reflection coefficient. As mentioned above when the value that is exactly equal to its characteristic impedance, so there is no discontinuity and signal is terminated to the ground with no reflections. But with short or open loads we have 100% reflection, but in these cases we have reflected signal negative or positive respectively.
2.8 Rise Time Effect on Reflections

When the rise time will become less than twice the delay (TD) of transmission line, it will have significant influence on the wave shape. On figures 2.10.1 and 2.10.2 we can see the effect that edge rate has on underdriven and overdriven transmission lines. It should be mentioned that how as much the wave shape changes as the rise time exceeds twice the delay of the line. When we have the edge rate twice the line delay, than the reflection from the source arrives before the transition from one state to another is complete.
Figure 2.10.1 Effect of a slow edge rate: overdriven case

Figure 2.10.2 Effect of a slow edge rate: underdriven
3.1 Time Domain Reflectometer

The technique called time domain reflectometer (figure 3.1.1) reveals the characteristic impedance of the line and also states the position and the type of each discontinuity along the line. With the help of this technique it possible to check the losses in the transmission line are series losses or shunt losses. In any case time domain reflectometer is the best measuring technique which gives you very clean information about the transmission system.

![Diagram of Time Domain Reflectometer](image)

Figure 3.1.1 Voltage vs time at a particular point on a mismatched transmission line driven with a step of height $E_i$

- 22 -
If we take classical case of transmission line in TDR in that case we have continuous structure of R’s, L’s and C’s (see figure 3.1.2). When we study the circuit carefully it is easy to determine that when we have infinitely long line and the R, L, G and C are known per unit length then we can come up with following equation:

\[ Z_{in} = Z_0 \sqrt{\frac{R + j\omega L}{G + j\omega C}} \]

here \( Z_0 \) is the characteristic impedance of the line.

So the voltage generated from voltage source will travel through transmission line till some x point in an infinite time, but the phase of voltage will lag behind the voltage introduced at the generator by an amount \( \beta \) per unit length. Moreover the voltage will be tapered off with an amount \( \alpha \) per unit length and that is because the series resistance and shunt conductance of the line. So the phase shift and the exhaustion will be defined by the constant which is called propagation constant \( \gamma \):

\[ \gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \]

Where \( \alpha \) is exhaustion in nepers per unit length and \( \beta \) is phase shift in radians per unit length. Now it is easy to define the velocity in terms of \( \beta \) at which signal travels down to the line:
The velocity of the propagation will reach the speed of light ($v_c$) in case when we have the transmission line with air dielectric. But for the common cases where we have dielectric constant $e_r$ then:

$$v_{\rho} = \frac{v_c}{\sqrt{e_r}}$$

### 3.2 Time Domain Reflectometer testing

In order to have more clear view to Time Domain Reflectometer let’s take a look at the Time Domain Reflectometer step reflection testing measurement, this testing method will give more details about the working performance of Time Domain Reflectometer. The block diagram of Time Domain Reflectometer is illustrated on figure 3.2.1.

<table>
<thead>
<tr>
<th>High Speed Oscilloscope</th>
<th>Device Under Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sampler</strong></td>
<td>$Z_L$</td>
</tr>
<tr>
<td><strong>Circuit</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Step Generator</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.2.1 Block diagram of Time Domain Reflectometer**

Trough the transmission system we have applied a positive incident wave which is produced by the step generator. Hence the applied step travels down to transmission line with the propagation velocity of the line. As long as we have both impedances equal (characteristic impedance and load impedance) to each other than we will not have any
reflection, so there will not be any wave reflected from the load and all these we can see on the display of oscilloscope. See figure 3.2.2.

But in case when the characteristic impedance and load impedance are not equal to each other than some part of the incident wave will be reflected. On the figure 3.2.3 we can see the result from oscilloscope display; here the reflected voltage wave is added to incident wave algebraically.

On figure 3.2.2 and 3.2.3 we have the oscilloscope display results for two cases when $E_r = 0$ and $E_r \neq 0$:

![Diagram for $E_r = 0$](image1)

**Figure 3.2.2 display plot for $E_r = 0$**

![Diagram for $E_r \neq 0$](image2)

**Figure 3.2.3 display plot for $E_r \neq 0$**

### 3.3 Locating Mismatches

As mentioned above the reflected wave can be easily identified because as we can see from the plots the reflected wave is separated from the incident wave in time. With the help of the separation time we can also determine the length of the transmission system from the controlling point to the mismatch. Let’s assume that “L” is the length between these two points:
Here \( v_p \) is the propagation velocity
\( T \) is the tie from controlling point to the mismatch and back

From this equation the propagation velocity can be calculated if we know the exact type of cables and the length of the cables are known.

### 3.4 Estimating Reflections

We have to pay attention also to the shape of the reflected wave because with the help of that we can determine the essence and also the magnitude of the mismatch. So on figure 3.4.1 is stated the four typical oscilloscopes display results and also the impedance \( e \) for the load liable for each.

With the help of following equation all these displays are clearly annotated:

\[
\rho = \frac{E_r}{E_i} = \frac{Z_L - Z_0}{Z_L + Z_0}
\]

As oscilloscope measures \( E_r \) and \( E_i \) that allows calculating \( Z_0 \) in terms of \( Z_L \) or vice versa.

(a) Open circuit termination \( (Z_L = \infty) \)

\[
Z_L \rightarrow \infty, \text{ hence } \frac{Z_L - Z_0}{Z_L + Z_0} = +1
\]

\( Z = \text{open circuit} \)
On the pictures illustrated above we can see the actual screen captures from the 86100A.

(b) Short circuit termination \(Z_L = 0\)

\[
\frac{1}{3} E_i \quad E_i \quad Z_L \rightarrow 2Z_0
\]

(c) Line terminated in \(Z_L = 2Z_0\)

\[
\frac{1}{3} E_i \quad E_i \quad Z_L \rightarrow \frac{1}{2}Z_0
\]

(d) Line terminated in \(Z_L = \frac{1}{2}Z_0\)

\[
\frac{Z_L-Z_0}{Z_L+Z_0} = -\frac{1}{3}
\]

\[
Z = \text{short circuit}
\]

For finite \(Z_0\)

\[
\frac{Z_L-Z_0}{Z_L+Z_0} = -1
\]

\[
Z_L = 2Z_0
\]

\[
\frac{Z_L-Z_0}{Z_L+Z_0} = \frac{1}{3}
\]

\[
Z_L = \frac{1}{2}Z_0
\]

**Figure 3.4.1** Different displays of TDR for typical loads
In the paragraphs above we were mostly discussing about the mismatches of Time Domain Reflectometer, the case when characteristic impedance is not equal with the load impedance. However, during the design of the Time Domain Reflectometer engineers have other problem also which is also very important and it needs to be considered. So often there are not only mismatches but also the discontinuities along the line. In order to have more clear view let’s take a look on figure 3.5.1.

![Figure 3.4.2 Open circuit and short circuit terminations screen captures](image)

3.5 Line with Discontinuities

The junction of two lines (both characteristic impedance $Z_0$) employs a connector of some sort. For this case we can assume that with the series of the line the connector adds a small indicator. There isn’t much deference between analyzing this discontinuity of the line and mismatched termination. In effect, one treats everything to the right of
“N” in the figure as an equivalent impedance in series with the small inductor and then calls this series combination the effective load impedance for the system at the point “N”? As in the right side of “N” the input impedance is \( Z_0 \), hence on the figure 3.5.2 we have the corresponding representation.

![Series R-L circuit the special case](image)

**Figure 3.5.2 Corresponding representation**

For the case mentioned above the oscilloscope display result is stated on figure 3.5.3:

\[
E_i \quad \tau = \frac{L}{2Z_0}
\]

**Figure 3.5.3 Series R-L circuit the special case**

### 3.6 Reckoning up cable loss

Time Domain Reflectometry technique is also useful for comparing losses in transmission line. On the one hand the cables where series losses predominate reflect a voltage wave with an exponentially rising characteristic; on the other hand cables where shunt losses predominate reflect a voltage wave with an exponentially-decaying characteristic. This is obvious when we look at the input impedance of the lossy line.

Input impedance is given by the below stated equation, If we assume that the lossy line is infinitely long:
In case when the major losses are the series losses, than G is very small compared with $\omega C$ so it can be neglected:

$$Z_{in} = Z_0 = \frac{R + j\omega L}{\sqrt{G + j\omega C}}$$

Recalling the approximation $(1 + x)^a \approx (1 + ax)$ for $x < 1$, $Z_{in}$ can be approximated by:

$$Z_{in} \approx \frac{L}{\sqrt{C}} \left(1 + \frac{R}{j\omega L}\right) \text{ when } R < \omega L$$

As the incident step leading edge made up almost entirely of high frequency components, than R is certainly less than $\omega L$ for $t = 0^+$. Therefore the above approximation for the lossy line, which looks like a simple series R-C network, is valid for a short time after $t = 0$. It turns out that this model is all that is necessary to determine the transmission line’s loss.

So the transmission line with series losses is illustrated in Figure 3.6.1, In terms of an equivalent circuit valid at $t = 0^+$.

Figure 3.6.1 A simple model valid at $t = 0^+$ for a line with series losses
The R series resistance is not constant with frequency as it is a function of skin depth of the conductor. Therefore it is hard to relate the initial slope with an actual value of R. But in any case when we want to compare conductors with different losses the magnitude of the slope is useful.

When shunt shunt losses predominate than for a conductor the similar analysis is possible. Below mentioned equation is the input admittance of the lossy cable:

\[ Y_{in} = \frac{1}{Z_{in}} = \sqrt{\frac{G + j\omega C}{R + j\omega L}} = \frac{G + j\omega C}{j\omega L} \]

We can write above mentioned equation for \( Y_{in} \) in a different way as \( R \) is assumed to be very small:

\[ Y_{in} = \sqrt{\frac{C}{L}} \left( 1 + \frac{G}{j\omega C} \right)^{1/2} \]

By approximating the same equation we will get:

\[ Y_{in} = \sqrt{\frac{C}{L}} \left( 1 + \frac{G}{j2\omega C} \right) \text{When } G < \omega C \]

On the figure 3.6.2 is shown the equivalent circuit at \( t = 0^+ \).

\[ Y_{in} = G' + \frac{1}{j\omega L'} \]

Figure 3.6.2 A simple model valid at \( t = 0^+ \) for a line with shunt losses
If we explain why $e_{in}^t$ behaves as it does, so it is quite simple, because in case of series losses the voltage wave traveling down the line accumulates more and more series resistance to force current through, so the line looks more and more like an open circuit as time goes on.

On the other hand for the shunt losses the current traveling down the line sees more and more accumulated shunt conductance to develop voltage across, so the input eventually looks like a short circuit.

### 3.7 Multiple Discontinuities

For Time domain Reflectometer we may say that it has an advantage because it can handle cases when there is more than one discontinuity. The example is illustrated on figure 3.7.1.

\[ Z_0 \neq Z_0' \neq Z_L \]
\[ \rho_1 = \frac{Z_0' - Z_0}{Z_0' + Z_0} = -\rho_1' \]
\[ \rho_2 = \frac{Z_L - Z_0'}{Z_L + Z_0'} \]

**Figure 3.7.1** Cable with multiple discontinuities

The result for the oscilloscope is stated on figure 3.7.2

\[ Z_0 > Z_0' < Z_L \]

**Figure 3.7.2** Accuracy decreases as you look further down a line with multiple discontinuities
The thing is that the reflections produced by two mismatches can be analyzed separately. So \( E_r \) is the reflected wave generated from the mismatch at the junction of two transmission lines:

\[
E_r = \rho_1 E_i = \left(\frac{Z_0' - Z_0}{Z_0' + Z_0} \right) E_i
\]

Same we can say about the mismatch at the load which also creates reflection and that is because of the reflection coefficient:

\[
\rho_2 = \frac{Z_L - Z_0'}{Z_L + Z_0'}
\]
4.1 Main Circuit

A Time Domain Reflectometer was designed with the given task. The whole circuit structure by block level is illustrated on figure 4.1.1 and by transistor level on figure 4.1.2.

As we can see the designed Time Domain Reflectometer includes 4 main blocks. But there is a difference between the circuit 4.1.1 and the circuit discussed above (Figure 3.2.1). As can be seen from figure 3.2.1 for signal detection is used a sampler circuit. The Sampler circuit contains an ADC (Analog to Digital converter). The
Figure 4.1.2 Time Domain Reflectometer by transistor level
idea is that ADC is converting reflected analog signal to digital. So the circuit used on the
figure 3.2.1 is measuring reflected wave in time domain. The circuit used in this project
doesn’t include any ADC, here the detection of the signal has been done with the help of
one capacitor and usual inverter. That is why this circuit is low power and much faster
compared with the circuit on figure 3.2.1 and also this circuit measure the time of the
wavefront; how far away is the short circuit.

First block is Pulse Generator, where we generate the first pulse which after will
travel through the transmission line. The generated first pulse is 1.2V.

The upcoming second part is the transmission line block. The signal generated by
pulse generator will travel through the transmission line it will be reflected back totally
as we have short circuit in the end of the transmission line by connecting it to the
ground. The length of the transmission line is 10cm and the impedance of the
transmission line is 50 Ohms.

The next block is pulse extension block. The main idea of having this part is to
catch the signal which is reflected back from the end of the transmission line and also to
generate the pulse with the fixed length. That means independently from the input
pulse length (signal coming from transmission line) it has to generate a pulse with the
fixed length. That was done with the help of edge triggered DFF which generates a pulse
only when it sees the rising edge of the input pulse.

The fourth one is the delay block. The use of the delay block is for generating very
short pulse.

The fifth and final block is the start up circuit which is for generating first pulse
for the circuit. As we know the full circuit has to oscillate itself but anyway we have to
generate the first pulse and then it will start to oscillate itself.
4.2 Simulations

As mentioned in chapters before in order to design the Time Domain Reflectometer the main and most important problem needs to be solved is the matching of the circuit (Impedance matching), otherwise the circuit will not work correct.

In this project that problem was the hardest one to solve. The way it has been done was the calculation of impedance of every point before connecting that point to some other device. Because when we exactly know what is the impedance of the point and we also know the impedance of the transmission line (50 Ohms) than it is easy to match them together. In case when they are different a resistor should be added in order to make it equal.

First the whole circuit was designed without using start up circuit. A $V_{\text{pulse}}$ was added and in the end when whole circuit was working, than the output and input were connected together, afterwards a start up circuit was added in order to generate first pulse.

As mentioned the most important thing is to match the circuit. That has been done with adding a DC voltage in “Genout” poin, in order to see the current. After having current and voltage the calculation result shows that in the output of the inverter (GenOut point) we have 25 Ohms. Now it is obvious that in order to connect the transmission line we need to add to the circuit a 50 Ohms resistor, so we will have 50 Ohms and that will be matched with the impedance of the transmission line. On figure 4.2.1 we can see the circuit which is connected to the transmission line.

Figure 4.2.1 Circuit connected with the transmission line
As we can see from figure 4.2.1 the transmission line is connected to the ground in order to provide the short circuit so the signal will travel through the transmission line till the end and then it will be reflected back. Hence, now the next step is to catch that signal and see the shape of the signal. So for catching the reflected back signal a capacitor was added in order to block DC voltage, after that two resistors are connected to the circuit, those resistors were connected as voltage divider, but the main idea of adding these resistors is to set DC voltage. The way it has been performed is illustrated on figure 4.2.2.

![Figure 4.2.2](image)

After adding capacitance and resistors the simulation results showed the following plot and this signal is the reflected signal from transmission line (see figure 4.2.3).

As we can see from the plot, except the main reflected pulse which we are going to use after, we have also some other reflections. As mentioned in theoretical chapters
that is called multireflections, it is mainly due to that the circuit cannot be matched ideally. However, this signal cannot be used for further simulations because the whole circuit will start to work not properly.

On the figure 4.2.2 there is an inverter in the end of the circuit this inverter in converting the reflected signal but the main purpose of that inverter is solving the problem of multireflections that we have. As we need only the first reflected pulse so with the help of changing the sizes of the inverter transistors the threshold voltage of the inverter will be changed in a way that only the first pulse will pass through the inverter and the rest small multireflections will not pass. Hence, in the output of the inverter we will have a signal which is perfect to use for further design. The output of the inverter is illustrated in figure 4.2.4:

![Reflected signal](image1)

**Figure 4.2.3 Reflected signal**

![Output of the inverter](image2)

**Figure 4.2.4 Output of the inverter**
4.3 DFF Design

The next and very important part after catching the reflected signal is to generate a pulse which will be used again for the input for whole circuit. That means we have to generate pulse and the length of the pulse should not be changed because of the input signal.

See figure 4.2.2. In the end of the circuit we have an inverter which cleans the signal from multireflections and the output of that inverter will be the input for other device which will generate a pulse. As mentioned above that device should generate pulse and the length of that pulse should be fixed and it should be independent from incoming pulse length. The main idea is to use generated signal again as an input for whole circuit. In order to achieve that we have to have kind of device which will generate a pulse when it sees the rising edge of incoming signal. For this reason used an edge triggered DFF was used(Figure 4.3.1).
Figure 4.3.1  Edge sensitive DFF added to the circuit
As we can see from the picture CLK is the input of DFF and that is the output of the inverter and the “dffout” is the output of the DFF were we had to see the generated pulse.

Here another problem was accrued; see figure 4.3.2 where we can see the input (clk) and the output (q) signal plots of DFF after the simulations.

![Figure 4.3.2 Input and output signals of DFF](image)

As we can see from the picture illustrated above the output signal is not the one we need. Furthermore, the device is working wrong. The main problem is that the output signal is not independent from input signal. It is obvious from the plots that when the DFF sees input pulse first edge it generates the signal rising edge and then when the next input signal is coming the DFF generates the falling edge of the output signal and vice verse. This means that the length of the output signal is dependent from the input signal.
Figure 4.3.3 TDR circuit with edge sensitive and reset input DFF.
With the help of changing the DFF circuit with other one which has a reset input, it became possible to reset DFF circuit anytime we need. See figure 4.3.3

As can be seen from the figure 4.3.2 the output signal is waiting for the next input pulse in order to fall down, but the main idea of reset is that we can force the output signal fall down if we have 1.2V on the reset of DFF, so it will reset the signal.

Anyway it is not so easy to perform because we need some time before putting the DFF on reset mode, otherwise we will not see the output signal at all. Since, to perform that kind of structure, a delay circuit was used for making a delay and after that delay we can put DFF on reset mode. The structure designed for having that delay is shown in figure 4.3.3.

The graphs after simulations are stated below (figure 4.3.4):

![Simulation results](image)

**Figure 4.3.4 Simulation results**
Now as we can see easily from the plots our DFF is generating a pulse the length of which is independent from the input pulse, so it sees the edge of the incoming pulse and generates output signal. It is obvious that for each “clk” we have separate pulse in the output of the DFF.

4.4 Start-up Circuit Design

As can be seen from block diagram stated on figure 4.1.2 the circuit has to work itself without applying any voltage source. Here comes out importance of designing start up circuit. The idea of designing such a circuit is to generate a first pulse which takes out the circuit from the initial stage to the oscillation stage. So the start up circuit will generate first pulse for the circuit and also when something happen with the circuit and it stops oscillating, after some time it has to generate pulse again. Consequently, start up circuit is not only for generating first stat pulse, but also it will provide the working performance of whole circuit.

The design of the start-up circuit has been done as following:

![Strat-up circuit](image)

*Figure 4.4.1 Strat-up circuit*
The whole circuit contains two transistors M1 and M2, two current sources and one capacitor (C1). It should be mentioned also that everything depends on the FB signal, which is a “feedback” coming from the circuit.

Two current sources are for the charging and discharging the C1 capacitor and M1, M2 transistors are switches. M1 is a PMOS transistor and M2 is a NMOS. So in case of initial stage, when the whole circuit does not start to work yet, than there is a low voltage on the FB point (no signal). Hence, M2 transistor will be closed and M1 will be open and the capacitor will start to charge. Here we need the help of first current source with the help of the capacitor will charge faster. After some time capacitor will generate a pulse (a falling edge, see figure 4.4.2):

![Generated pulse](image)

As capacitor generates the first pulse the circuit will start to oscillate itself. See figure 4.4.3.
As can be seen from the figure 4.4.3 the capacitor is charging and after some time when it generates the pulse, the plot is falling down and after we have zigzag structure. The main idea is that when the circuit starts to oscillate we have high and low voltages so the M1 and M2 transistors are switching very fast. Consequently, the time is not enough to charge the capacitor again. Hence, when M1 is open it wants to charge and then after some nanoseconds M1 is closed and M2 is open, so it discharges again. This is why we have that zigzag structure. The second current source is stated on the circuit for that reason and the value of the current source is 900mA so this is enough to discharge 3pF capacitor in a couple of nanoseconds.

Same picture will be in case when the circuit stops oscillating for some reasons; in that case we will have low stage again on the FB point, so the M1 transistor will be open and the C1 capacitor will start to charge till the point where it generates the first pulse again.

The simulation results for whole circuit are illustrated on figure 4.4.4:
### 4.5 Frequency Simulations

One of the most important parts is also to check out the frequency of the signal. The idea is that when the length of the transmission line is changed the frequency also should be changed. As the designed circuit could be used for different purposes, that means it is mandatory to have the results frequencies for different transmission line lengths. Simulation results are illustrated below on figure 4.5.1:

![Frequency Simulations Graph](image)

**Figure 4.5.1 Frequency for different transmission line lengths**

On the picture the “x” axes is the delay of transmission line and the “y” axes is frequency. The simulations were done for different delays of transmission line, as for different delay times we have different lengths of transmission line. The corresponding results are stated in table below:

<table>
<thead>
<tr>
<th>Delay</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ns</td>
<td>170MHz</td>
</tr>
<tr>
<td>2ns</td>
<td>120MHz</td>
</tr>
<tr>
<td>3ns</td>
<td>90MHz</td>
</tr>
<tr>
<td>4ns</td>
<td>80MHz</td>
</tr>
<tr>
<td>5ns</td>
<td>70MHz</td>
</tr>
</tbody>
</table>

**Table 4.5.1 Simulation results**
5.1 Conclusion

To sum up, the Printed electronics, i.e. electronic components manufactured using printing technology is a promising technology for future low cost high volume applications.

The designed circuit in this project is for use in printed electronics applications, so it is important to know the advantages of the printed electronics.

For printed electronics all we need is just a paper, which can be thinner than 1mm. Moreover, this technology is environmentally friendly, as if the paper becomes useless it is possible to treat it as normal waste paper.

The printed electronics are also very safe as no one would be injured by paper. Also the products are very flexible and they can be folded, so those products may be placed everywhere.

Most importantly those products are very cheap, as no need of using some chemical liquids or cut of machines during production process. In addition printed transmission lines are very low power consumption compared with same circuit on PCB boards.

5.2 Future Plans

Printed electronic is a new technology, which is environmental friendly. But it has many deficiencies and need investment for researching.

- Firstly, tuning the circuit in order to have better working performance and find most suitable structure.

- Try to attract customer interest in order to get investments and make the circuit available for real use applications
5.3 REFERENCES


2. Transmission Line (TL) Effects


5. Moreno, T., Microwave Transmission Design Data, Dover, 1958,

6. Rizzi, P., Microwave Engineering Passive Circuits, Prentice Hall, 1988,

7. Waves and Impedances on Transmission Lines, EEE 194 RF

8. REAL TIME MONITORING OF INFRASTRUCTURE USING TDR TECHNOLOGY:
   PRINCIPLES Kevin M. O’Connor and Charles H. Dowding

9. Time-Domain Reflectometry & S-Parameter Channel Models, Sam Palermo Analog & Mixed-Signal Center Texas A&M University


12. CONTROLLED IMPEDANCE AND TIME DOMAIN REFLECTOMETRY (TDR),

13. Characteristic Impedance of Lines on Printed Boards by TDR, ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES

14. Time domain reflectometry measurement principles and applications, Scott B. Jones, Jon M. Wraith and Dani Or

15. Time Domain Reflectometry Theory, Application Note 1304-2