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Extraction of two wire Loop topology using Hybrid Single Ended Loop Testing

M. Bharathi[1], A.Amsaveni[2], S. Ravishankar[3]

[1,2]Kumaraguru College of Technology, Coimbatore, India
[3]R. V. College of Engineering, Bangalore, India

Abstract: Performance of the Digital Subscriber Line (DSL) depends on the line topology and the noise power spectral density (PSD). Single ended loop testing (SELT) is the preferred and economical method for identifying the loop topology. In this paper SELT based on a combination of Correlation Time Domain Reflectometry (CTDR) and Frequency Domain Reflectometry (FDR) is proposed to identify the topology of a two wire line. In CTDR, complementary codes are used to probe the line and the reflections are correlated with the probe signal. For lines with multiple discontinuities, a Maximum Likelihood principle is developed along with data de-embedding technique. The prediction accuracy of the CTDR is limited but the main advantage is, it does not need any prior knowledge of the loop. To improve the accuracy of prediction, FDR with optimization algorithm is developed. This Hybrid method has the advantage of predicting the loop accurately without any prior knowledge of the loop. An improvement to the hybrid method to overcome the issues associated with the initial prediction for multiple discontinuity loops is implemented. The proposed CTDR and FDR use the existing modem for probing the line which avoids the need for additional hardware. As the SELT measurements are done online, the effect of cross talk and AWGN is considered. The developed algorithm is tested for standard ANSI loops and the results shows good prediction capability of this algorithm. However, when there are more number of discontinuities, the contribution of the far end reflection in the received echo signal is very feeble and this limits the prediction accuracy of far end discontinuity.

Keywords: SELT; Correlation Time Domain Reflectometry (CTDR); Frequency Domain Reflectometry (FDR); Hybrid method; Complementary Codes; Optimization.

Prepoznava topologije dvožičnih povezav v naročniški zanki s hibridno metodo testiranja na enem kraju

Izvleček: Učinkovitost digitalne naročniške linije (DSL) je odvisna od njene topologije in šuma moči sprektralne gostote. Za določevanje topologije zanke je priporočeno in ekonomično uporabiti testiranje na enem kraju (SELT). V članku je za določevanje topologije predlagan SELT na osnovi korelacijske reflektometrije v časovni domeni (CTDR in reklektometrije v frekvenčni domeni (FDR). Predlagana metodologija uporablja obstoječ modem in ne zahteva dodatne strojne opreme. SELT meritve so opravljene v živo, zato smo upoštevali tudi vplive presluhov in AWGN. Algoritem je testiran za standardne ANSI zanke in rezultati kažejo na njegovo dobro sposobnost napovedovanja.

Ključne besede: SELT; CTDR; FDR; hibridna metodologija; komplementarne kode; optimizacija

** Corresponding Author's e-mail: Bharathi.m.ece@kct.ac.in*

1 Introduction

The service provider has to estimate the Quality of Service (QoS) afforded over a subscriber loop under realistic circumstances. Apart from the data rate, QoS also prescribes the delay in the transmission (in ms), the packet loss and Bit Error Rate (BER). QoS is a function of subscriber line conditions which includes the line topology and noise Power Spectral Density (PSD). A double ended loop measurement allow easy estimation of loop impulse response and the noise PSD, but needs a test device at the far end of the loop and is not economical prior to a service commencement. An economical SELT would require a reuse of the network operator's central office (CO) side DSL modem resources to perform measurements [1].

The physical loop consists of gauge changes, bridge taps and loop discontinuities that result in change of characteristic impedance. When a signal is injected through the line, reflections (echo) will be generated from all these discontinuities. These generated echoes are analysed to extract the location and the type of discontinuity. S. Galli et al [2-5] have used pulse TDR to characterize the loop. A pulse is considered as a probe signal and is transmitted through the loop and the reflections produced by each discontinuity are observed in time. The time domain reflection which contains the signature of the loop is then analyzed to predict the loop topology. Clustering of the TDR trace [3-4] and the use of statistical data [5] are included to reduce the time and to increase the accuracy respectively. These techniques provide a good estimation of the loop but are computationally intensive and cannot be easily implemented in current DSL modems. A more practical method described by Carine Neus et al [7] uses one port scattering parameter S11 in time domain to estimates the loop topology. The S11 measurement is however done off line with a vector network analyzer over the entire band width [6]. David E. Dodds [8, 9] has proposed FDR for identifying the loop impairments. The measurement phase uses a signal generator to probe the line up to 1.3MHz in steps of 500 Hz and the reflections are coherently detected. However if there are multiple discontinuities close to each other (<100m), detecting all discontinuities in a single step is not possible. If the discontinuities are far from each other the order of variation of the reflection makes it difficult to predict all the discontinuities in a single step.

SELT and Double Ended Loop Testing (DELT) are together employed in [10], to predict the loop topology. In [11] Genetic Algorithm (GA) based optimization method is used to estimate the line topology. In this paper [11], S11 is measured from CO end using SELT probing and the transfer function (H) measured from both the ends using DELT are considered as inputs. An initial solution (topology) is assumed and multi objective optimization algorithm is used to obtain the final optimum solution. For both these methods additional equipment are needed in the measuring phase and the measurement cannot be done on line.

SELT estimation is performed in two phases. In measurement phase the reflections are captured; termed as SELT – PMD function in G.SELT [12] and a second phase called as interpretation phase when analysis is done for topology estimation; termed as SELT-P function in G.SELT. The measurement phase of the proposed method reuses the blocks of the DSL modem and hence only a small code is needed that can be easily compiled into any modem. In this step the line is sounded sequentially once by employing CTDR and next by employing FDR. In the interpretation phase, the first step consists in analyzing CTDR results to obtain an approximate estimation of the distance and the type of the discontinuities [14, 15]. The topology learning from the CTDR application is used to generate an FDR data for the estimated loop. In the second step of the interpretation phase the generated FDR data is compared with a target (measured) FDR data in mean squared sense to arrive at an exact estimate of the loop topology. The analysis of measured data may be performed in the modem to a limited extent or offline where more computing resourcesare available.

Section 2 of this paper details the Correlation Time Domain Reflectometry (CTDR) for the initial loop topology estimation. In section 3, measurement and interpretation phase of Frequency Domain Reflectometry (FDR) is discussed. Section 4 gives the result of topology estimation of standard ANSI loops and the concluding remarks are drawn in section 5.

2 Correlation time domain reflectometry (CTDR)

Reflections from each discontinuity are characterized by the length and type of discontinuities present in the loop. The possible echo paths of a line with single bridge tap is shown in Figure1.

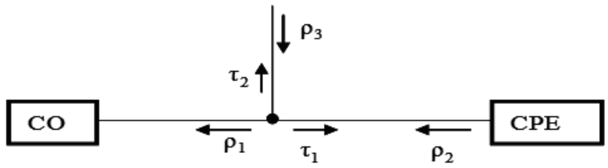


Figure 1: Representation of a loop with possible echo paths

Spread spectrum (SS) techniques using the existing modem can be used for identifying the characteristics of the loop without scarifying the response resolution. In the proposed CTDR method, data is loaded in all the subcarriers at a time and the reflections are used for the estimation of the loop topology. The Digital Subscriber Line (DSL) modem can work in full duplex mode. It can simultaneously transmit and receive data with an additional firmware. This firmware helps in the modification of the filter coefficients present in the front end of the modem. CTDR method does not need any prior knowledge of the loop but the accuracy of prediction is limited due to the variation in propagation velocity with frequency and the gauge of the copper medium. A mathematical model for the time domain echo is developed based on the two port network theory.

2.1 Mathematical model for Time domain Echo Signal

The proposed TDR method uses existing Discrete Multi Tone (DMT) modem with its bit loading algorithms. The received echo signal *r(t)* for a probe signal *p(t)* is given by

$$r(t) = \sum_{i=1}^{M} e_r^{(i)}(t - T_i) + N_0(t) \tag{1}$$

Where,
M - number of discontinuities in the line,
$N_0(t)$ - noise present in the channel
T_i - time of arrival of the i[th] echo
$e_r^{(i)}(t)$ - echo generated by the i[th] discontinuity given by

$$e_r^{(i)}(t) = p(t) * h_{ep}^{(i)}(t) \tag{2}$$

Where,
p(t) - probe signal
$h_{ep}^{(i)}(t)$ - impulse response of the i[th] echo path.

Complementary codes which have good autocorrelation property are used as probe signals *p(t)* [14] and the received echo signal *r(t)* is correlated with the probe signal.

$$W(t) = r(t) \otimes p(t) \tag{3}$$

$\otimes$ – represents correlation operation. The signal *w(t)* contains the signature of the loop and can be used to estimate the loop topology.

2.2 Analysis of CTDR signal

Correlated signal will have its peak when transmitted signal has completed its round trip of any discontinuity. The time difference between the peaks and the propagation speed of the (ν) medium are used to estimate the distance of the discontinuity. Complementary codes are used as probe signal [14, 15]. With complementary codes, the correlated signal is 2*N* times stronger and the noise is build up by a factor $\sqrt{2N}$. Thus SNR improvement with complementary code CTDR to direct impulse probe scheme is $\sqrt{2N}$. To further reduce the effect of AWGN noise, averaging over number of symbols is performed. Noise reduction by averaging technique and the use of complementary codes improves the overall SNR significantly.

The attenuation and reflections in the loop reduces the strength of the reflected signal from each discontinuity and the peaks from distant discontinuities are not clear in the correlated signal. To overcome this limitation, Maximum Likelihood (ML) principle [14] with data de-embedding is incorporated. ML principle is employed to identify the nature and type of discontinuity one after the other. Data de-embedding process masks the reflections of the identified discontinuity in the overall echo signal to unravel the signatures of the unknown discontinuities. Thus by incorporating the de-embedding process, overall predictability of the CDTR method is enhanced. This improved CTDR method illustrated in Figure 2 has the following steps:

1. Estimate the i[th] discontinuity location from the peak position of *W(t)* (equation 3).
2. Hypothesize discontinuity by considering all the possible topologies. $\{T_j^{(i)}\}$ is the set of all possible topologies at step *i* and *j = 1,2…N, N* is the number of possible topologies based on the magnitude of the reflection coefficient. Each possible topology consists of the previously identified line segments and the hypothesized discontinuity followed by an infinite loop section. The unknown segment of the loop after the hypothesized discontinuity is represented by an infinite loop section so as to eliminate any reflection from the unknown section.
3. Simulate echo for all the possible topologies. $\{h_j^{(i)}(t)\}$ is the simulated echo signal for each of the topologies in $\{T_j^{(i)}\}$, at step *i*.
4. Generate the error vector $e_j^{(i)}$ in the localized time interval t_1 to t_2, corresponding to the hypothesized topologies $\{T_j^{(i)}\}$ at step *i*.

$$e_j^{(i)} = \sum_{t1}^{t2} r(t) - h_j^{(i)}(t) \tag{4}$$

5. Choose the maximum likelihood topology by comparing the calculated error (*e*). The corresponding simulated signal is considered as $h^{(i)}(t)$ and the topology is $T^{(i)}$.
6. If the selected topology is bridge tap, set BT=1and continue.
7. The de-embedded signal after the removal of i[th] discontinuity is $d^{(i+1)}(t) = r(t) - h^{(i)}(t)$.
8. Generate the corresponding correlated signal $w^{(i+1)}(t)$
9. If there is no peak in $w^{(i+1)}(t)$ then the hypothesized topology $T^{(i)}$ is the estimated topology. Else continue.
10. i=i+1.
11. Estimate i[th] discontinuity location from the peak position of $w^{(i)}(t)$.
12. If BT=1 generate $T^{(i)}$ by including a bridge tap with $T^{(i-1)}$) and continue. Else go to step 2.
13. Generate corresponding $h^{(i)}$.
14. De-embedding: $d^{(i+1)}(t) = r(t) - h^{(i)}(t)$
15. Set BT=0;
16. Go to step 8.

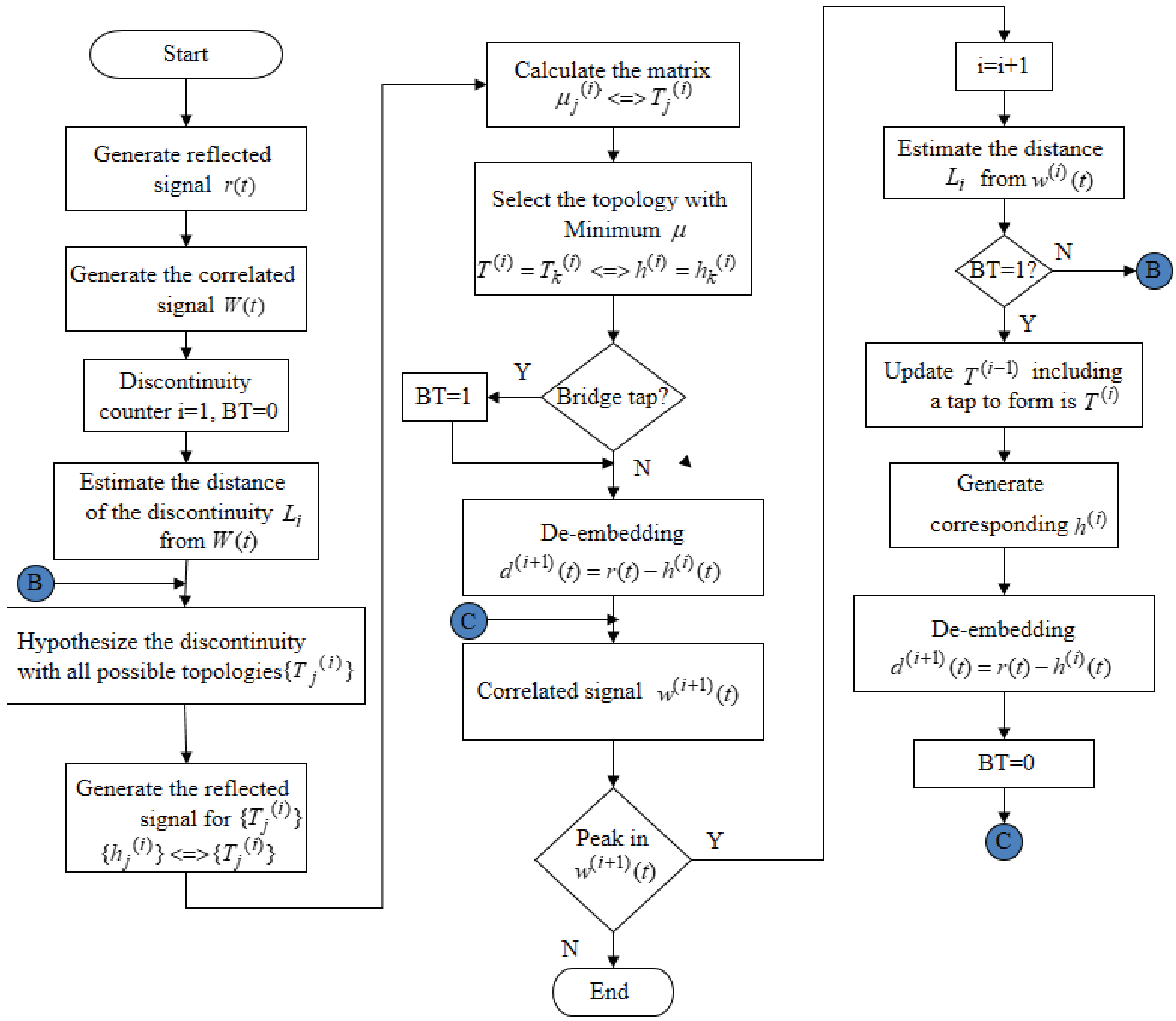


Figure 2: Step by step Maximum Likelihood approach with De-embedding

3 Frequency domain reflectometry (FDR)

A FDR measurement method is based on single tone excitation. Each tone in a DMT symbol is sounded individually and its echoes are captured using the DSL Modem. As explained above, additional firmware at the modem helps to extract the reflections. The total received echo signal is the sum of echo signals of individual tones and is used in the analysis phase to predict the loop topology. The mathematical model for the echo signals in frequency domain is developed and is used in the optimization algorithm.

3.1 Mathematical model for FDR

The received echo signal for the nth tone along with the effect of noise is given by,

$$R(f_{n)} = \sum_{i=1}^{M} \left(R^{(i)}(f_n) + N_o(f_n) \right) \tag{5}$$

Where,
M- number of echo paths in the loop
$N_0(f_n)$ - noise in the echo signal.
$R^{(i)}(f_n)$ - received signal from the ith echo path when nth tone is sounded given by,

$$R^{(i)}(f_n) = S(f_n) Hecho^{(i)}(f) \tag{6}$$

Where,
$S(f_n)$ - spectrum of the transmitted data (Energy only in the nth bin)
$Hecho^{(i)}(f)$ - transfer function of the ith echo path given by,

$$Hecho^{(i)}(f) = F(\tau^{(1)}, \tau^{(2)}, \ldots \tau^{(i-1)}) H^{(i)}(f) \rho^{(i)}(f) \quad (7)$$

Here $F(\tau^{(1)}, \tau^{(2)}, \cdots \tau^{(i-1)})$ is a frequency dependent function that includes the transmission coefficients of all the discontinuities preceding the i^{th} discontinuity and $\rho^{(i)}(f)$ is the reflection coefficient of the i^{th} discontinuity. $H^{(i)}(f)$ is the line transfer function [13,14].

$$H^{(i)}(f) = e^{-\gamma Li} \quad (8)$$

Where,
Li - length of the i^{th} echo path.
γ - Propagation constant which is a function of frequency, given by

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

The total received echo signal is sum of echo signals for all the transmitted tones.

$$R(f) = \sum_n R(f_n) \quad (9)$$

*R(f)*is the received echo signal from all discontinuities as seen at the receiver FFT output and contains information about these discontinuities. The frequency range of the input signal determines the predictable range and resolution of the FDR method. The minimum measurable distance (resolution) increases with range of frequency as higher range will have complete periodic information even for a shorter length. Amplitude of the echo signal depends on the attenuation in the line and attenuation is doubled due to the round trip travel along the loop. The lower tones (low frequency tones) suffer less attenuation compared to the higher tones and are essential for longer loops. Thus there is a need to balance the contrasting requirement between reach and resolution.

The initial topology estimated by CTDR method is used as a guess topology and optimization is carried out based on the guess topology.

3.2 Optimization method

The steps involved in this algorithm are
Simulate FDR echo signal for the initial topology (Φ) estimated using Correlation Time Domain Reflectometry $\hat{R}(\Phi, f_n)$, using equation (5).

Obtain the FDR echo signal $R(f_n)$ from measurements.
Calculate the cost function (MSE)

$$MSE = \left(\sum_{n=1}^{N} \left| \hat{R}(\Phi, f_n) - R(f_n) \right|^2 \right) \quad (10)$$

Obtain the accurate line topology by minimizing the cost function using Nelder-Mead simplex optimization algorithm.

Nelder-Mead optimization algorithm [16] iteratively improves Φ in terms of line segment lengths until the best solution (close match) is found.

4 Simulation results

The developed Hybrid method is used for the prediction of the ANSI standard telephone lines [13] shown in Figure 3. The parameters used for the simulation of CTDR and FDR are tabulated in Table.1.

Test loops 1 to 5 are plain lines with different lengths and gauge. End of line is the only discontinuity and it is considered as an open termination with reflection coefficient is 1 and the correlated signal will have a positive peak. FDR signal for a plain line will be a decaying sinusoidal wave satisfying the equation [18,19]

$$R(f) = a_1 \exp(-a_2 f) \cos(a_3 f + a_4) \quad (11)$$

Where, a1, a2, a3and a4 depend on the gauge, length and the termination.

Table 1: Parameters used for Simulation

Parameters	Values in CTDR	Values in FDR
Total transmitted power	21dBm as specified in DSL standard [13]	-36.5dBm/Hz as per PSD mask specified in DSL standard[13]
No of bits per tone	2 bits, 4QAM	2 bits, 4QAM
Tone considered	6 - 511	6 – 110 (One tone at a time)
Crosstalk noise [13]	24 ADSL NEXT and FEXT	24 ADSL NEXT and FEXT
AWGN PSD	-130 dBm/Hz	-130 dBm/Hz
Velocity of Propagation (VoP)	0.63 C (C- speed of light)	--
Number of frames	10000	--

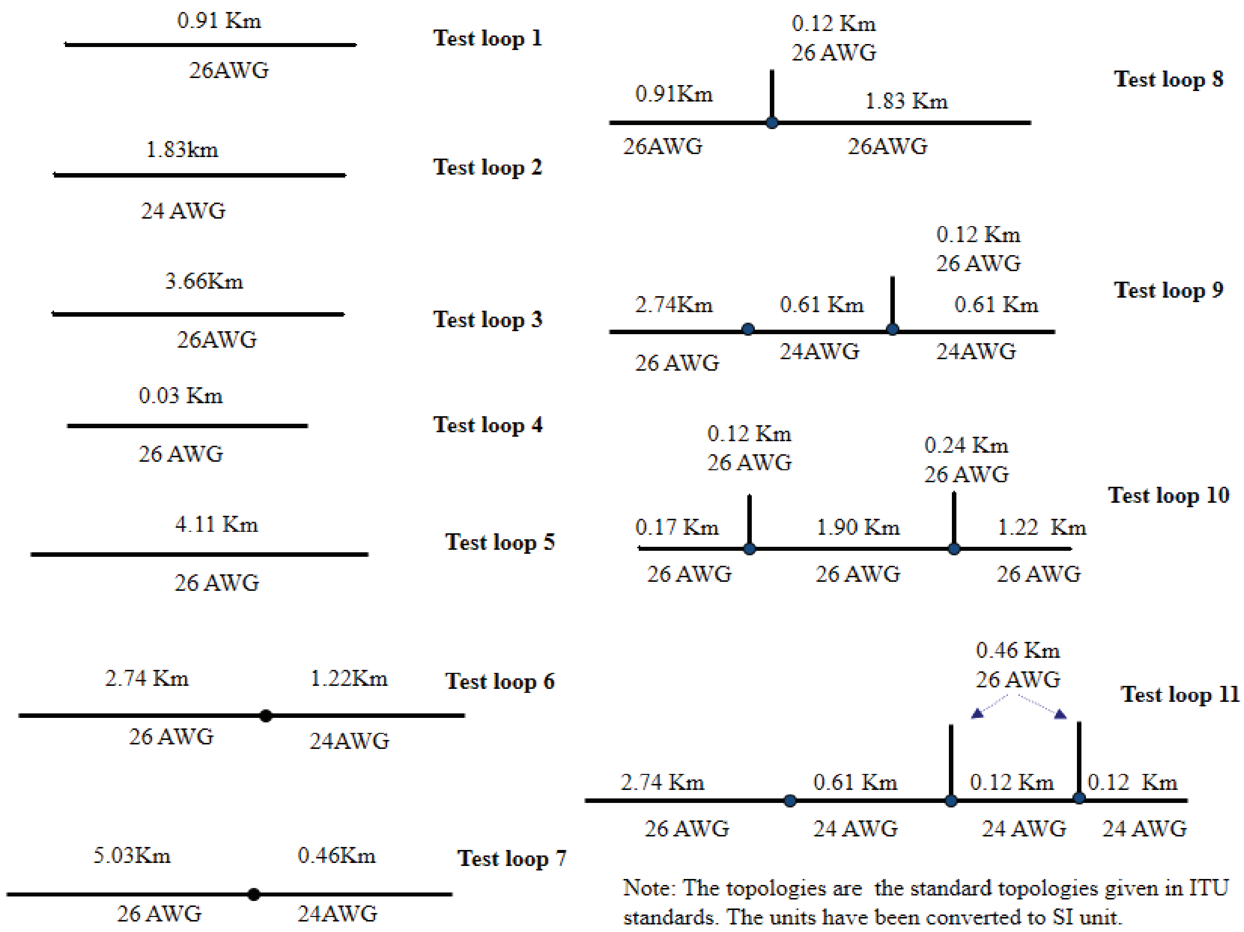


Figure 3: TEST loops

The waveforms and the analysis of plain line are explained with test loop 2 which is a medium reach (1.83 Km, 24 AWG) with open end. For this loop, the variation of correlation amplitude with reach is shown in Figure 4. The peak value of the signal is positive (0.002398) at a distance 1.80 Km.

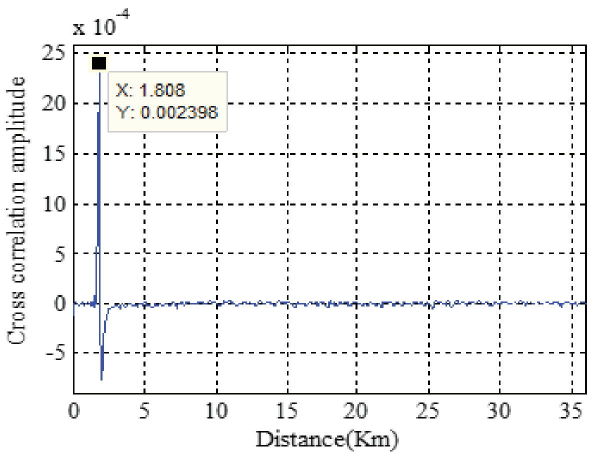


Figure 4: Correlation amplitude Vs distance for test loop2

The possible topologies with the above prediction (1.80 Km, open end) and calculated error (e) are tabulated in Table 2, from which the line is understood as 1.80 Km of 24 AWG.

Table 2: Possible topologies for Test loop 2

Sl. No	Hypothesized discontinuity	possible topology	MSE
1	End of loop (open)	1.80 Km line, 26 AWG	2.40e-3
2	End of loop (open)	1.80 Km line, 24 AWG	**8.35e-5**

The frequency domain received echo signal for this loop (Test loop 2) is shown in Figure 5. The FDR is a decaying sinusoidal waveform.

With the initial guess of 1.80 Km, 24AWG (Predicted using CTDR), the optimization algorithm is used and Figure 6 shows the variation of mean square error with the line length for both gauges and the line is predicted as 1.83 Km, 24 AWG line.

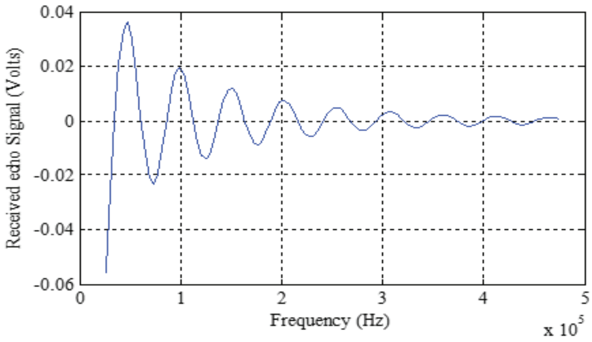


Figure 5: Frequency Domain Reflectometry signal for test loop2

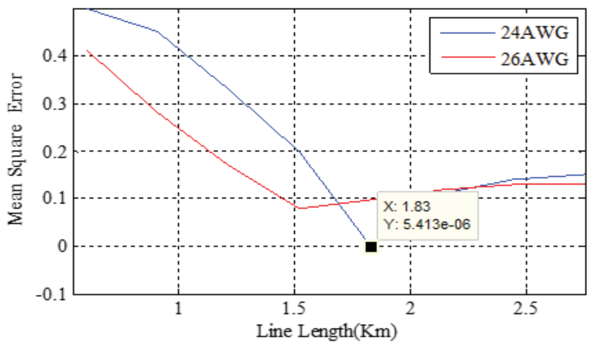


Figure 6: Error curve for test loop2

Test Loops 7 to 11 are loops with one or more discontinuities. For lines with multiple discontinuities, depends on the type of discontinuity and its length, the dominant portion of the received signal varies. Following are the observations made with different discontinuities.

The influence of the gauge change in the final signal is much lesser due to its low reflection coefficient of ~ -0.03.

The reflection coefficient at the bridge tap is ~ -0.3. Hence the influence of the received signal from the bridge tap is predominant.

When the numbers of discontinuities are higher than two, the reflection from the later segments of the loop is not felt in the overall received signal and these segments are not predicted with good accuracy.

In summary, the magnitudes of transmission and reflection coefficients of different discontinuities are tabulated in Table 3 [2].

The analysis of lines with multiple discontinuities is explained with test loop 11. Figure 7 shows the correlated signal amplitude with distance for test loop 11. Negative peak with amplitude 3.19e-6 at 2.88 Km indicates negative reflection coefficient and gauge change or bridge taps are the possible topologies.

Table 3: Magnitude of Transmission and Reflection coefficients of different discontinuities

Sl. No.	Type of Discontinuity	Reflection Coefficient	Transmission Coefficient
1.	Gauge Change	0.03	0.97
2.	Bridge Tap	0.33	0.33*
3.	End of Loop (Open)	1	0

* one wave will travel along the BT and other wave will travel along the next loop section

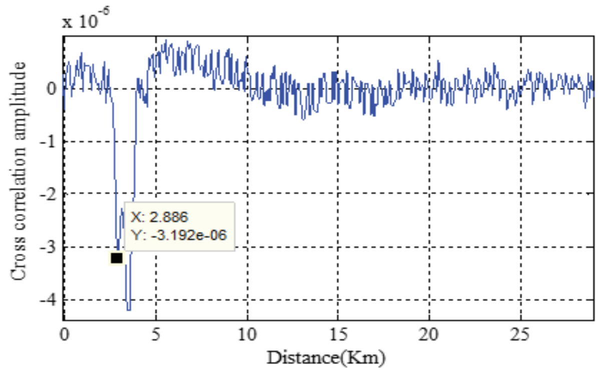


Figure 7: Correlation amplitude Vs distance for test loop 11

All the possible topologies with this observation and the mean square error (e) between the simulated echoes for these possible topologies with the received echo are listed in Table 4. From this table, topology with gauge change (S No1) is identified as the correct topology till first discontinuity ($T^{(1)}$).

The echo due to the identified first segment is removed from the received echo. Figure 8(a) shows the de-embedded signal $w^{(2)}(t)$ after removing the reflection from identified topology ($T^{(1)}$). Negative reflection at 3.49 Km is inferred as bridge tap and the length of the second line segment is 0.7Km (3.58Km- 2.88 Km). Construction of all possible topologies (including the identified topology segments) is listed in Table 5. The MSE helps in identifying the gauge of the line segments. With identifying the tap as 26 AWG, $w^{(3)}(t)$ is generated and the length of the bridge tap is estimated as 0.18Km (3.76Km – 3.58 Km). De-embedding the echo based on the identified loop segments results in $w^{(4)}(t)$ from which the third segment of loop is estimated as 0.61Km (4.19 Km-3.58 Km) with open end. In $w^{(5)}(t)$ there are no peaks visible and CTDR estimated topology is shown in Figure 8(d). The de-embedding process is shown in Figure 8(a-c).

Table 4: Possible topologies for first discontinuity (Test loop 11)

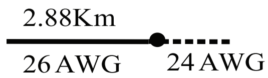
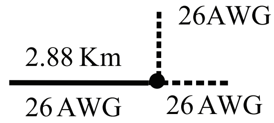
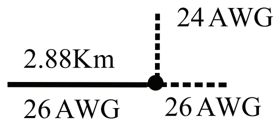
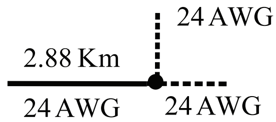
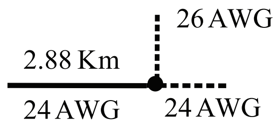
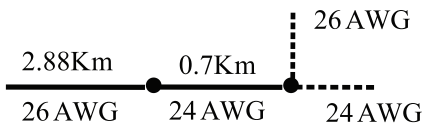
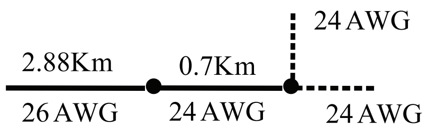
Sl. No	Hypothesized discontinuity	Possible topology (dotted line indicates infinite length)	MSE
1	Gauge change		1.05e-6
2	Bridge tap (Taps with Open end)		1.11e-5
3	Bridge tap (Taps with Open end)		1.25e-5
4	Bridge tap (Taps with Open end)		1.11e-4
5	Bridge tap (Taps with Open end)		1.03e-4

Table 5: Possible topologies at second discontinuity for test loop 11

Sl. No	Hypothesized discontinuity	possible topology (dotted line indicates infinite length)	MSE
1	Gauge change followed by bridge tap(Taps with Open end)		4.04e-6
2	Gauge change followed by bridge tap (Taps with Open end)		4.40e-6

The CTDR estimation for test loop11 is not complete. This is due to the very less contribution of the far end reflection in the overall received signal. With this as the initial guess, FDR prediction converged to MSE error of 0.0028. For lines with more discontinuities, the CTDR prediction of the number of discontinuities may not be complete. As the FDR step in the hybrid method focuses only on the accuracy of the segment lengths, there is no possibility of correct prediction if the initial guess is incomplete in the number of discontinuities. This limitation is found to be serious for complex topologies. The hybrid method is improved to address this issue by adding a discontinuity in the initial guess from CTDR step when the MSE error after global search is higher than the set threshold value. This additional modification is shown in Figure 9. As the CTDR is capable of predicting first two discontinuities and from practical understanding the maximum number of discontinuities is not more than 4, this outer loop is set with a maximum limit of two.

This issue of non convergence for test loop 11 with FDR is due to wrong specification of number of discontinuities as the initial guess. The improved hybrid method is employed. The converged line topology with improved hybrid method is shown in Figure 10.

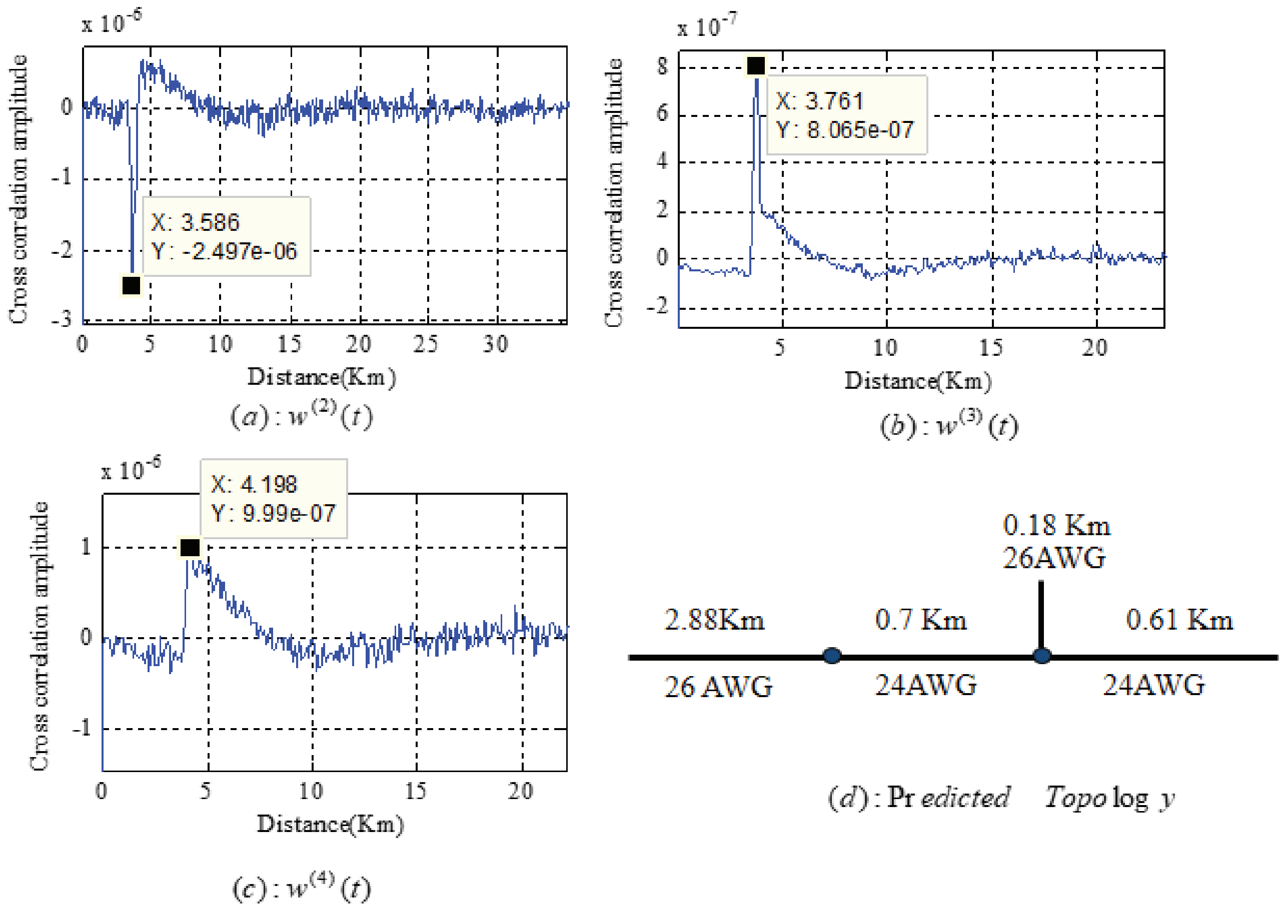


Figure 8: De-embedded signal for test loop 11

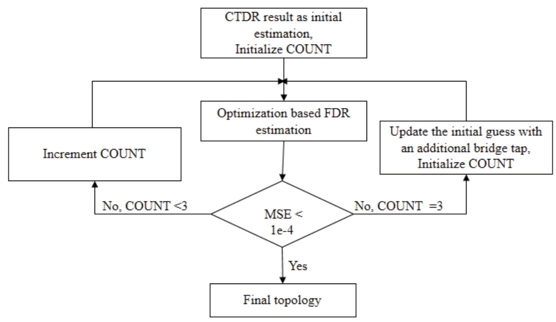


Figure 9: Improved Hybrid method

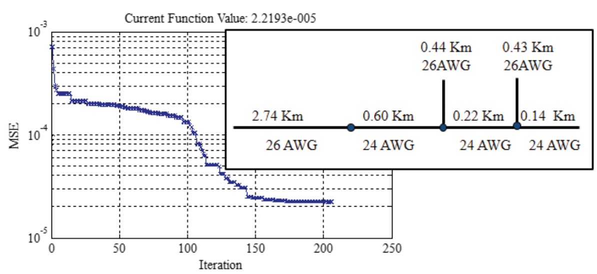


Figure 10: The convergence for test loop 11

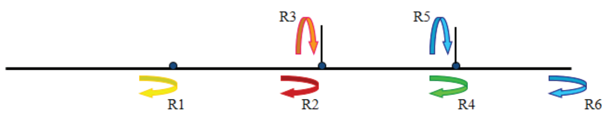


Figure 11: Reflection analysis of test loop 11

The summary of results for all the test loops is presented in Table 6.

The variance in Table 6 is very small which indicates that the same optimum topology was obtained with repeated trails. The estimation error is less in the case of plain loops and loops with one or more discontinuities. For test loop 11, the first two line segments and the first bridge tap length are predicted with good accuracy but the segment 3, 4 and tap2 length are not accurate. Figure 11 shows the schematic representation of the reflection from each discontinuity. Strength of the reflection from each junction is calculated based on the reflection and transmission coefficients for comparison. Table 7 compares the % contribution of each reflection in the received echo signal as per the transmission and reflection coefficients listed in Table 3. Signal attenuation and gauge are not considered in this calculation as the focus is to quantify the effect of

Table 6: Summary of results using Hybrid method for Telephone Lines

<table>
<tr><th>Test Loop</th><th>Actual Loop Topology (Km)</th><th>Initial Estimate using CTDR (Km)</th><th>% error</th><th>Estimated Topology Using CTDR and FDR (Km)</th><th>% error</th><th>% Variance in the estimation</th></tr>
<tr><td>Test Loop1</td><td>0.91, 26 AWG</td><td>0.94, 26 AWG</td><td>3.33</td><td>0.91, 26 AWG</td><td>--</td><td>0</td></tr>
<tr><td>Test Loop2</td><td>1.83, 24 AWG</td><td>1.80, 24 AWG</td><td>1.16</td><td>1.83, 24 AWG</td><td>--</td><td>0</td></tr>
<tr><td>Test Loop3</td><td>3.66, 26 AWG</td><td>3.87, 26 AWG</td><td>5.73</td><td>3.66, 26 AWG</td><td>--</td><td>0</td></tr>
<tr><td>Test Loop4</td><td>0.03, 26 AWG</td><td>--</td><td>--</td><td>0.03, 26 AWG</td><td>--</td><td>0</td></tr>
<tr><td>Test Loop5</td><td>4.11, 26 AWG</td><td>--</td><td>--</td><td>4.11, 26 AWG</td><td>--</td><td>0</td></tr>
<tr><td rowspan="2">Test Loop6</td><td>Segment1 – 2.74, 26 AWG</td><td>2.75, 26 AWG</td><td rowspan="2">4.06</td><td>2.74, 26 AWG</td><td rowspan="2">0.25</td><td rowspan="2">0.04</td></tr>
<tr><td>Segment 2 -1.22, 24 AWG</td><td>1.38, 24 AWG</td><td>1.21, 24 AWG</td></tr>
<tr><td rowspan="2">Test Loop7</td><td>Segment1- 5.03, 26 AWG</td><td>--</td><td rowspan="2">--</td><td>5.01, 26 AWG</td><td rowspan="2">0.55</td><td rowspan="2">0.3</td></tr>
<tr><td>Segment 2- 0.46, 24 AWG</td><td>--</td><td>0.45, 24 AWG</td></tr>
<tr><td rowspan="3">Test Loop8</td><td>Segment 1 -0.91, 26 AWG</td><td>0.94, 26 AWG</td><td rowspan="3">4.1</td><td>0.91, 26 AWG</td><td rowspan="3">--</td><td rowspan="3">0.1</td></tr>
<tr><td>Bridge tap-0.15, 26 AWG*</td><td>0.17, 26 AWG*</td><td>0.15, 26 AWG*</td></tr>
<tr><td>Segment 2- 1.83, 26 AWG</td><td>1.90, 26 AWG</td><td>1.83, 26 AWG</td></tr>
<tr><td rowspan="4">Test Loop9</td><td>Segment 1- 2.74, 26 AWG</td><td>2.84, 26 AWG</td><td rowspan="4">6.3</td><td>2.74, 26 AWG</td><td rowspan="4">0.24</td><td rowspan="4">0.1</td></tr>
<tr><td>Segment2 -0.61, 24 AWG</td><td>0.57, 24 AWG</td><td>0.61, 24 AWG</td></tr>
<tr><td>Bridge tap-0.15, 26 AWG*</td><td>0.18, 26 AWG*</td><td>0.15, 26 AWG*</td></tr>
<tr><td>Segment 3-0.61, 24 AWG</td><td>0.70, 24 AWG</td><td>0.60, 24 AWG</td></tr>
<tr><td rowspan="5">Test Loop10</td><td>Segment 1 - 0.17, 26 AWG</td><td>0.18, 26 AWG</td><td rowspan="5">7.3</td><td>0.17, 26 AWG</td><td rowspan="5">0.27</td><td rowspan="5">0.2</td></tr>
<tr><td>Bridge tap 1 - 0.12, 26 AWG*</td><td>0.08, 26 AWG*</td><td>0.12, 26 AWG*</td></tr>
<tr><td>Segment 2- 1.90, 26 AWG</td><td>2.01, 26 AWG</td><td>1.90, 26 AWG</td></tr>
<tr><td>Bridge tap 2 - 0.24, 26 AWG*</td><td>0.26, 26 AWG*</td><td>0.24, 26 AWG*</td></tr>
<tr><td>Segment 3 -1.22, 26 AWG</td><td>1.31, 26 AWG</td><td>1.21, 26 AWG</td></tr>
<tr><td rowspan="6">Test Loop11</td><td>Segment 1 – 2.74, 26 AWG</td><td>2.88, 26 AWG</td><td rowspan="6">--</td><td>2.74, 26 AWG</td><td rowspan="6">3.06</td><td rowspan="6">1.2</td></tr>
<tr><td>Segment 2 – 0.61, 24 AWG</td><td>0.7, 24 AWG</td><td>0.60, 24 AWG</td></tr>
<tr><td>Bridge tap 1 – 0.46, 26 AWG*</td><td>0.18, 26 AWG*</td><td>0.44, 26 AWG*</td></tr>
<tr><td>Segment 3- 0.15, 24 AWG</td><td>0.61, 24 AWG</td><td>0.22, 24 AWG</td></tr>
<tr><td>Bridge tap 2 – 0.46, 26 AWG*</td><td>--</td><td>0.43, 26 AWG*</td></tr>
<tr><td>Segment 3 -0.15, 24 AWG</td><td>--</td><td>0.14, 24 AWG</td></tr>
</table>

*Indicates Bridge Tap

individual reflections on the final echo. Around 89% of the received echo is contributed by the reflections R1, R2 and R3. Even though R4 reflection is considered as 6 %, due to the higher distance of travel, attenuation will be higher and hence net overall contribution in the received signal will be much lesser than 6%. R5 and R6 have 2% weightage in the received signal even without considering the attenuation effect. This results in very feeble contribution in the measured echo. Hence accuracy of these line segments, in the predicted topology does not influence MSE to a significant level. This explains the reason for higher prediction error in the segments 3, 4 and Tap 2.

Analyses are conducted to study the improvement in prediction ability with increase in the strength of the probe signal PSD (by 3 and 6 dBm/Hz). As shown in Table 8, prediction ability improved with these cases. However, it must be noted that as per ITU standards [13], signal strength increase beyond 3 dBm/Hz is not recommended as it induces crosstalk noise in other lines. So the allowed strength of the probe signal is -33.3 dBm/Hz.

5 Conclusion

The combined CTDR and FDR method is developed for the extraction of loop topology of two wire telephone lines. CTDR can be employed where there is no initial knowledge of the loop. But the accuracy of CTDR estimation is limited. On the other hand, FDR method can predict the topology with higher accuracy but requires a reasonable initial knowledge of the topology. The pro-

Table 7: Reflection strength contribution (test loop11)

Reflection	Weightage of transmission and Reflection coefficients in the received signal (Excluding the attenuation effect)		
	Sequence of approximate reflection and transmission coefficients	Total	% contribution in the received signal (Ri/∑Ri)
R1	0.03	0.03	6.0
R2	0.97*0.33*0.97	0.3104	62.2
R3	0.97*0.33*1*0.33*0.97	0.1024	20.52
R4	0.97 *0.33*0.33*0.33*0.97	0.0338	6.7
R5	0.97*0.33*0.33*1*0.33*0.33*0.97	0.0112	2.2
R6	0.97*0.33*0.33*1*0.33*0.33*0.97	0.0112	2.2
∑Ri		0.499	

Table 8: Test loop 11 prediction summary with increased power

	Actual length (Km)	Predicted length with -36.5 dBm/Hz(Km)	Predicted length with -33.3 dBm/Hz(Km)	Predicted length with -30.3 dBm/Hz(Km)
Segment 1 (R1)	2.74	2.74	2.74	2.74
Segment 2 (R2)	0.61	0.59	0.60	0.61
Tap 1@ junction 2 (R3)	0.46	0.43	0.44	0.44
Segment 3 (R4)	0.15	0.28	0.22	0.17
Tap 2 @ junction 3 (R5)	0.46	0.23	0.43	0.47
Segment 4 (R6)	0.15	0.35	0.14	0.16

posed improved hybrid algorithm combines the advantage of both the methods and accurately estimates the loop topology without any initial knowledge about the loop. Maximum Likelihood procedure with de-embedding is used in this paper to mask the strong reflections after identifying the discontinuities. This helps in estimating the far end discontinuities which has minimum contribution in the overall reflected signal. Simulation results of standard ANSI loops shows that the error in the prediction is less than 0.3% for lines with one or two discontinuities. For lines with more number of discontinuities the prediction accuracy is around 3% due to the feeble contribution of far end reflections in the received signal. This proposed method has the significant advantage in the measurement phase as measurement can be directly implemented on the DSL modem with a minimal additional firmware. The interpretation of the measured data can be carried out either online or offline.

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