Single Ended Loop Topology Estimation using FDR and Correlation TDR in a DSL Modem

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***Abstract*— The broadband capability of a DSL is dependant on the copper access network. Single Ended Loop Testing (SELT) is the most preferred and economical way in estimating the copper loop topology. The combined use of complementary code based Correlation Time Domain Reflectometry (CTDR) and Frequency Domain Reflectometry (FDR) for accurate loop topology estimation is presented in this paper. The advantage of the proposed method is that the measurement is done by reusing most of the firmware modules in a typical DSL broadband modem without affecting other pairs in the bundle. Since the measurement is done in real time the effect of cross talk and AWGN have also to be considered. In this proposed method approximate loop estimation is obtained from CTDR measurements. An optimization algorithm is then used to predict a more accurate loop topology from the CTDR predicted loop. Employing FDR measured data and the FDR data of the predicted topology, an objective function is defined. The objective function is then minimized using Nelder-Mead multivariable optimization method to get an accurate loop estimate. Tests carried out on typical ANSI loops shows good prediction capability of the proposed method. No prior knowledge of the network topology is required in this process.**

Keywords*— Central Office, Digital subscriber line (DSL), Frequency domain Reflectometry (FDR), Correlation time domain Reflectometry (CTDR), Loop qualification, Optimization.

I. Introduction

Network operators supporting triple play services over wire line need to have an exact knowledge of subscriber loop topology to commit a specified quality of service (QoS). Double ended loop measurements allow easy estimation of loop impulse response and the noise PSD, but needs a test device at the far end of the loop and are not economical prior to a service commencement. An economical method would require a reuse of the network operator's central office (CO) side ADSL2 or VDSL2 modem resources to perform measurements from the CO side only.

The physical loop consists of gauge changes, bridge taps and loop discontinuities that result in a change of characteristic impedance. The generated echo from these discontinuities when a signal is injected into the physical loop is analysed to extract details of location and the type of discontinuity. S. Galli et al [1-4] have employed pulse TDR based techniques 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 analysed to predict the loop topology. Clustering of the TDR trace [2-3] and the use of statistical data [4] 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 [6] uses one port scattering parameter S_{11} in time domain and estimates the loop topology. The S_{11} measurement is however done off line with a vector network analyser over the entire band width [5]. David E. Dodds [7, 8] has proposed FDR for identifying the loop impairments. In the measurement phase a signal generator is used to probe the line up to 1.3 MHz 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 may not be 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 estimation process is performed in two phases. The measurement phase during which CTDR and FDR measurements are captured and a second phase termed as interpretation phase where the analysis is done. In this paper the analysis is performed in two steps for accurate loop topology identification. In the first step CTDR method is used for an approximate estimation of the distance and the type of the discontinuities [9]. The topology learning from the CTDR application is used to generate an FDR data. In a second step the generated FDR data is compared with a target FDR measured data in a mean squared sense to arrive at an exact estimate of the network topology. The measurement phase of the proposed method reuses the blocks of the current DSL modem and hence only a small code is needed that can be easily compiled into any modem. No separate test equipments or tools are required and the measurement is done online without disturbing the other services in the bundle. The analysis of measured data is performed in an interpretation phase in the modem to a limited extent or offline where more computing resources are available. Good predictability has been observed for a variety of ANSI loops with different reach and with multiple bridge taps [19].

The reminder of this paper is organized as follows. Section II deals with the CTDR method using complementary codes. Use of optimization algorithm for improving accuracy is dealt in section III & IV. Section V presents simulation results for the defined test loops.

II. Correlation Time Domain Reflectometry

Spread spectrum (SS) techniques afford a possibility of providing measurements with improved SNR without sacrificing response resolution. Proposed CTDR method uses the DMT modem with its bit loading algorithms [11] for measurement. A Spread spectrum probe signal $p(t)$ is transmitted through a loop with an echo transfer function h(t) and correlated with its echo signal $v(t)$ at the receiver to obtain the correlated signal $W(t)$ that is expressed as,

$$W(t) = p(t) \otimes v(t) = p(t) \otimes (k.p(t) * h(t)) \quad (1)$$

$$W(t) = k.(p(t) \otimes p(t)) * h(t) \quad (2)$$

Operator * represents convolution operation and $\otimes$ represents correlation operation. If the auto correlation of the probe signal can be approximated as delta function then

$$W(t) = k.\{ (L.\delta(t)) * h(t)\} \quad (3)$$

Here, L is the number of elements in the code.

The position of the cross correlation peak used to estimate the location of discontinuity (d) is given by

$$d = \frac{v.t_{\max}}{2} \quad (4)$$

Where, v is the velocity of propagation in the twisted pair and $t_{\max}$ is the peak position.

When the discontinuities are closely spaced it is difficult to distinguish the cross correlation peaks. This problem is addressed by using successive decomposition in this paper. After identifying each discontinuity (i) in a successive manner, an auxiliary topology ($Aux^{(i)}$) is formed which consists of all the previously identified discontinuities followed by an infinite loop section. The reflection due to this auxiliary topology (r_i) is generated and is removed from the total reflection $v(t)$ to get a de-embedded TDR trace D_i.

$$D_i = v(t) - r_i$$

The trace D_i consists of echoes from the rest of discontinuities in the line and is correlated with the input signal $p(t)$ to arrive W_i. W_i is the correlated signal after removal of echoes from the known discontinuities and hence brings out the next peak and discontinuity. This process is continued until there is no identifiable peak in the resultant signal. In this way after identifying each discontinuity the reflection due to the identified discontinuity is removed from the total reflection to enhance the predictability of the following discontinuities.

In this implementation complementary codes are used as a probe signal. Complementary codes are set of codes whose out of phase autocorrelation sums to zero. So the sum of the auto correlation of the two member sequence is a delta function [10].

$$A_k \otimes A_k + B_k \otimes B_k = 2L\delta_k \quad (5)$$

Where, δ_k is the delta function and A_k, B_k are the complementary code pairs of length L.

A 2L Complementary code is generated from its corresponding L element code by appending as shown in equation 6 [10]. Starting with a one element Golay code A=1 and B=1 the higher order Golay codes are derived as

$$\begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \rightarrow \begin{Bmatrix} 1 & 1 \\ 1 & -1 \end{Bmatrix} \rightarrow \begin{Bmatrix} 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & 1 \end{Bmatrix} \quad (6)$$

A complementary code of $L = 2^K$ is employed with K=10. Unipolar version of each of the complementary codes (A_{uni}, B_{uni}) [10] and its one's complementary form (A'_{uni}, B'_{uni}) is generated and these 4 codes are used to probe the line. Tone numbers 0-511 are loaded with 2 bits per tone with this L element code pair.

A. *Application of Complementary codes for loop topology estimation*

The steps involved in using the complementary codes for the loop topology estimation is shown in Fig.1.

1. Generate complementary codes A_k and B_k.
2. Generate the unipolar version and its one's complemented form for A_k and B_k.
3. For A_{uni}, simulate the reflected signal ($A_{uni} * h_k$) where, h_k is the impulse response of the channel.
4. For A'_{uni}, simulate the reflected signal ($A'_{uni} * h_k$).
5. Subtract $X_K{}^A = A_{uni} * h_k - A'_{uni} * h_k$.
6. Correlate $Y_K{}^A = X_K{}^A \otimes A_k$
7. Repeat steps 3-6 for the second Golay sequence to obtain $Y_K{}^B$.
8. Sum $Y_K = Y_K{}^A + Y_K{}^B$.

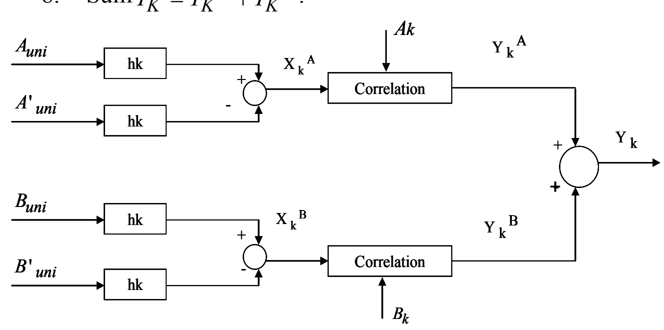

Fig.1. Functional diagram of Complementary CTDR for loop testing.

The auto correlation of the Golay code used in our simulation (K=10) is shown in the Fig.2. Ideally the auto correlation of the individual sequences (A_k, B_k) has side lobes but gets cancelled when added together. The peak of added signal will be 2L, Where L is the length of the sequence. For a non ideal system finite side lobes will be always present. Fig.2 also shows that at zero phase shifts the peak amplitude doubles and the inner figure shows a decaying out of phase auto correlation of the sum.

The effect of AWGN (-140dbm/Hz) and cross talk is added in the simulation as the measurement is done online. Cross talk is a slowly varying signal across the symbols and so gets cancelled due to the subtraction of the reflected signal (step 5 &7) shown in Fig.1. To mitigate the effect of AWGN noise, averaging over number of symbols is carried out. This averaging improves the signal to noise ratio (SNR) and hence increases the dynamic range.

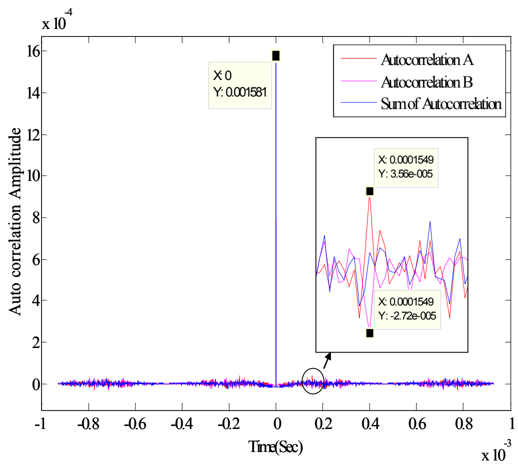

Fig.2. Auto correlation of the complementary codes

The accuracy of CTDR estimated topology is limited due to the variation in the velocity of propagation with frequency and with gauge. The predicted line topology from CTDR (Φ) contains length and gauge of all the line sections and is used as an initial estimate for the FDR based optimization method. The FDR received signal for the predicted topology Φ is simulated using the mathematical model described in the next section.

III. Model for the FDR received signal

The received echo signal is a function of the reflection (ρ) and transmission (τ) coefficients at each discontinuity.

The reflection coefficient (ρ) [16] is

$$\rho(f) = \frac{Za - Zb}{Za + Zb} \tag{7}$$

Where, Za and Zb are the frequency dependent characteristic impedance before and after the discontinuity. Similarly, τ is given by [16]

$$\tau(f) = \frac{2Za}{Za + Zb} \tag{8}$$

In the above equations, ρ and τ varies with frequency as the characteristic impedance is a function of frequency which is given by [18],

$$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{9}$$

The frequency dependant RLCG parameters in the above equation are obtained empirically as described in [18] and used in our computation for the transfer function of the 24 AWG and 26 AWG UTP lines. In the equations that follow we assume that the transmitted signal is a Discrete Multitone signal with 'N' tones conforming to the tone spacing and bandwidths as detailed in the DSL standards [11, 12].

The observed reflected signal along with the effect of noise, when the n^{th} tone is sounded is given by

$$R(f_n) = \sum_{i=1}^{M} \left(R^{(i)}(f_n) + No(f) \right) \tag{10}$$

Here $R^{(i)}(f_n)$ is the received signal from the i^{th} echo path when the n^{th} bin is sounded.

$No(f)$ is the noise power spectral density.

M is the number of echo paths in the loop

Further

$$R^{(i)}(f_n) = S(f) Hecho^{(i)}(f) \tag{11}$$

Where $S(f)$ is the power spectrum of the transmitted data and the $Hecho^{(i)}(f)$ is the transfer function of the i^{th} echo path and is given by

$$Hecho^{(i)}(f) = F(\tau^{(1)}, \tau^{(2)}, ...\tau^{(i-1)}) H^{(i)}(f) \rho^{(i)}(f) \tag{12}$$

Here $F(\tau^{(1)}, \tau^{(2)}, ...\tau^{(i-1)})$ is a frequency dependant 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 transfer function of the round trip path. The total received signal is sum of received signal of over all the tones.

$$R(f) = \sum_n R(fn) \tag{13}$$

IV. FDR Optimization

The prediction accuracy of the CTDR estimated loop is improved using FDR based optimization method. Nelder-Mead algorithm is chosen for this optimization as it can solve the multidimensional unconstrained optimization problems by minimizing the objective function. Tone numbers 6-110 is sounded with two bits in each tone using FDR. The steps involved in this algorithm is

1. Simulate FDR received signal for the guess topology $R(\Phi, fn)$.

2. Obtain an FDR measurement $(\hat{R}(fn))$.
3. Calculate the objective function (RMS error)

$$OE = \left(\sum_{n=1}^{N} \left| R(\Phi, fn) - \hat{R}(fn) \right|^2 \right) \qquad (14)$$

4. Obtain the accurate line topology by minimize OE using Nelder-Mead simplex optimization algorithm.

Nelder-Mead optimization algorithm iteratively improves Φ in terms of line segment lengths until the best solution (close match) is found. This algorithm works with constructing vectors with updating each variable (Each line segment lengths) of Φ, one at a time by increasing 5%. Initial Simplex consists of the newly created 'n' vectors along with Φ. The algorithm updates the simplex repeatedly until the best solution is found. Nelder-Mead algorithm has a limitation that it can converge to local minima. To overcome this local minima problem optimization is performed with a different initial guess whenever the objective function value is greater than 1e-4.

V. SIMULATION RESULTS AND DISCUSSION

The two step procedure described in section II and IV respectively is summarized below and is used for the estimation of the loop topology of typical ANSI loops.

A. *Correlation TDR*

In step 1, time domain reflected signal is correlated with the input signal to estimate the line discontinuities Tones 0-511 are sounded with 2 bits in each tone using the existing DSL modem. The received signal is correlated with the input signal and then analysed (Section II) to estimate the loop topology. The peak amplitude of the correlated signal depends on the length of the line and the reflection coefficient at the discontinuity. Fig.3. shows the variation of the peak amplitude with length for an open termination (reflection coefficient=1) for 24 and 26 AWG. For an estimated length, from the peak amplitude of the correlated signal, the magnitude of the reflection coefficient is calculated.

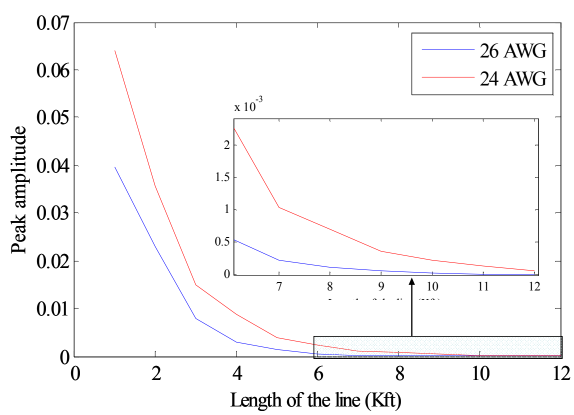

Fig.3. Peak amplitude variation of the reflected signal with line length

B. *FDR*

Estimated loop topology from CTDR is specified as the initial guess for step 2. Frequency domain reflection is obtained by sounding tones 6- 106. Using Nelder-Mead optimization algorithm guess topology is improved till convergence is achieved.

The flowchart of the proposed method is shown in the Fig.4.

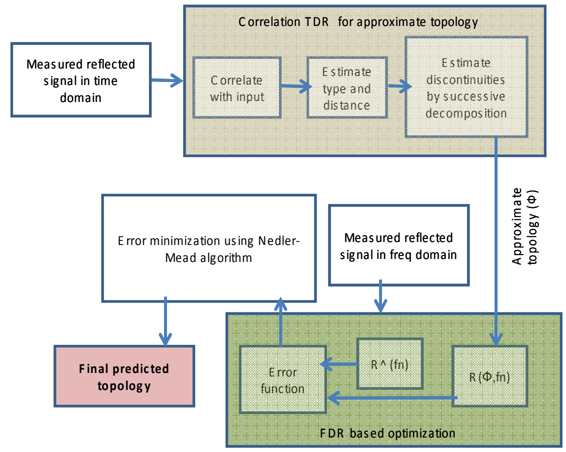

Fig.4. Flow chart of the proposed method

Test loops are defined to emulate all possible scenarios as per ITU recommendation 996.1[19] and are given in Fig.5 that include a variety of reach, gauge change and bridge taps. The applicability of the method is tested in the presence of -140 dbm/Hz AWGN and the cross talk defined in [11].

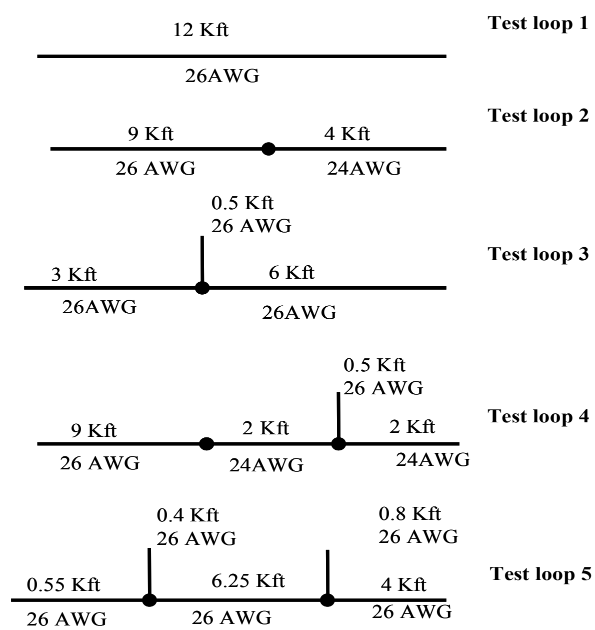

Fig.5. Test loops

Test loop 1: Correlation results in amplitude versus time lag is converted to the desired units of amplitude versus distance and is used in this analysis. For test loop 1 the distance versus correlation amplitude is shown in Fig. 6. The main lobe amplitude of the correlated signal is very less in the order of 1e-6. From the peak position the distance estimated is 12.71Kft which is 5% higher than the actual line length. From the amplitude of the peak the reflection coefficient is identified as 1(from Fig.3). The estimated topology is 12.7Kft line with open end.

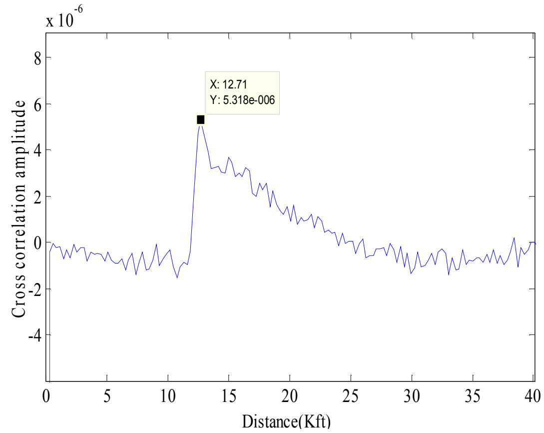

Fig.6. Distance Vs correlation amplitude for test loop 1

The CTDR topology is used as initial guess for FDR based optimization. The FDR signal for test loop 1 is shown in Fig.7. It is observed that the signal amplitude is low in the order of 1e-3 and the rate of decay is steep. While later part of the signal is seen as flat line in Fig.7, in the local scale, clear cycles are observed. Optimization algorithm is used with 12.71 Kft as an initial guess. Fig.8 shows the variation of mean square error with the line length for both 26 and 24 AWG. Based on this the line is declared as 26 AWG 12.0001 Kft line. The RMS error value is for this estimation is 4.83e-6.

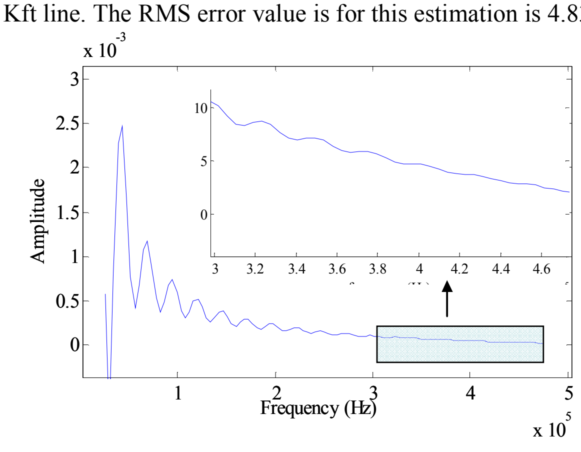

Fig.7. FDR signal for test loop1

Test loop2: Fig. 9 shows the correlation amplitude variation with distance for test loop2. The amplitude of the peak at 9.322Kft is -3.54e-6 for which the reflection coefficient is calculated as -0.05 and hence this is a gauge change. (The reflection coefficient of gauge change is -0.03). The location of the second peak is at 13.56 Kft (length of the second loop section is 4.24 Kft) with a peak value 2.04e-6. According to the practical cabling guidelines, the cables at CO end is of 26 AWG followed by 24 AWG later. So CTDR estimated loop is: 9.32 Kft of 26AWG followed by 4.24 Kft of 24 AWG and is shown in Fig.10. This is used as an initial topology for step2.

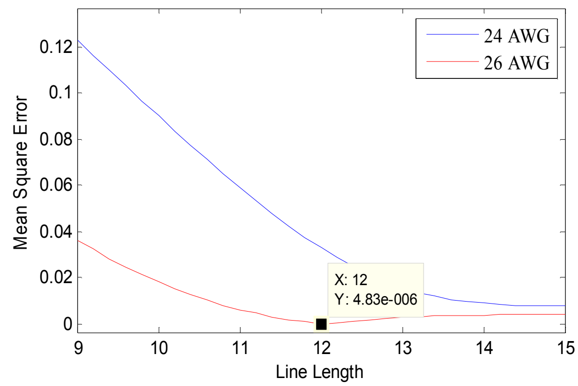

Fig.8. Error signal for test loop1

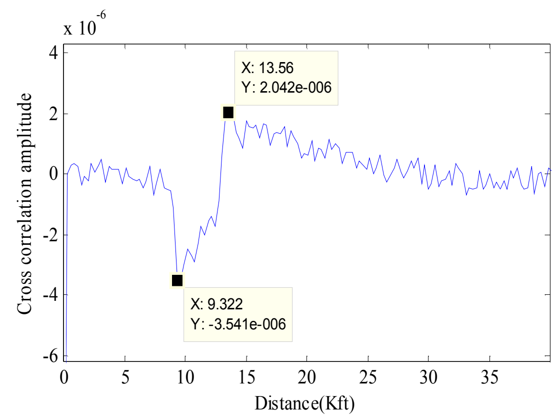

Fig.9. Distance Vs correlation amplitude for test loop2

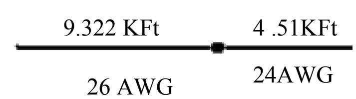

Fig.10. CTDR estimated topology for test loop 2

The FDR reflection for this test loop is shown in Fig.11. The contribution of the reflection from gauge change in the overall reflection is less due to the very low reflection coefficient of gauge change. The error curve shown in Fig.12 clearly shows the influence of the 2nd reflection in the error function. With optimization algorithm, the line topology is estimated as 9.0003 Kft in series with 3.999 Kft with an RMS error of 6.9e-6. The convergence of the optimization function is shown in Fig.13. It is observed that the error reduces monotonically from the first guess proves the stability of this algorithm and the number of iterations for convergence depends on the closeness of the initial guess.

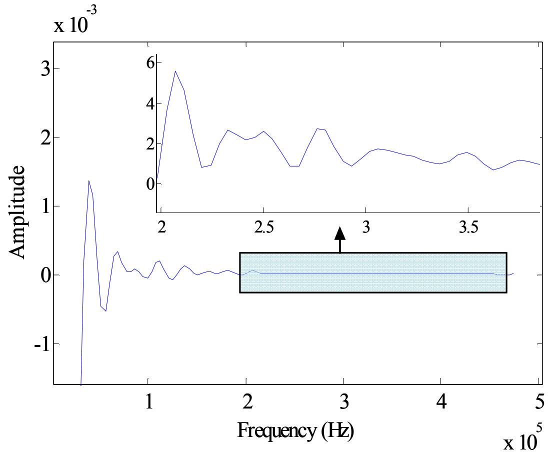

Fig.11. FDR signal for test loop2

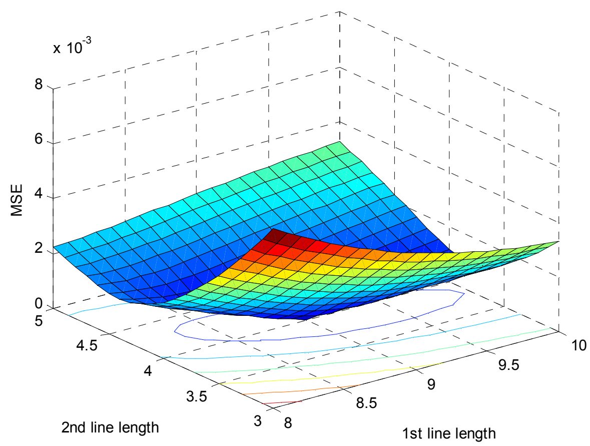

Fig.12. Error plot for test loop 2

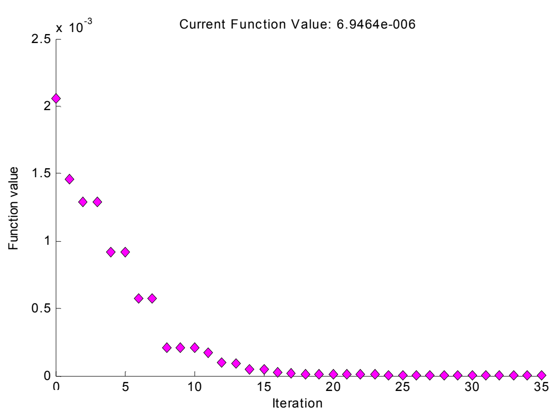

Fig.13. Error value Vs the number of iteration

Test loop 3: Distance versus correlation amplitude for test loop 3 is shown in Fig.14. A bridge tap has two reflections: one from the location of bridge tap with reflection coefficient of -0.3 and the other from the open end of the bridge tap with reflection coefficient equal to 1. Hence a negative peak followed by positive peak within a very short distance is expected. The amplitude value of the first peak at 3.107 Kft is -0.001976 which corresponds to the reflection coefficient -0.27. From the next peak location, the length of the bridge tap is estimated as 0.29 Kft. Auxiliary topology ($Aux^{(1)}$), difference signal (D_1) and its correlated signal (W_1) is generated for this identified topology and is shown in Fig.15. From this signal, the location of the next discontinuity is found at 9.47Kft (Second segment: 6.37 Kft). Further de-embedding predicts no significant peak and hence the line topology is estimated as: a bridge tap at 3.107 Kft followed by 6.37 Kft open end. The length of the bridge tap is 0.29

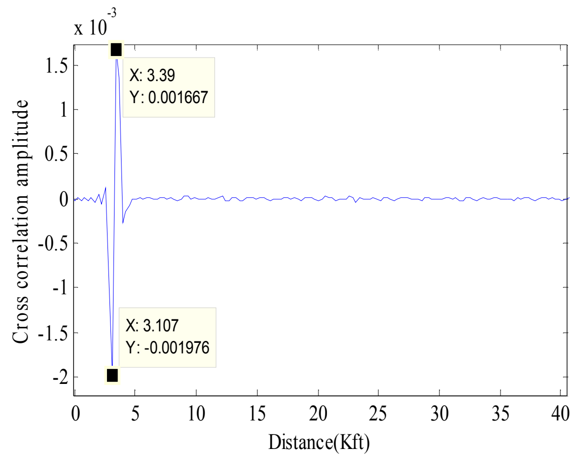

Fig.14. Distance Vs Correlation amplitude for test loop 3

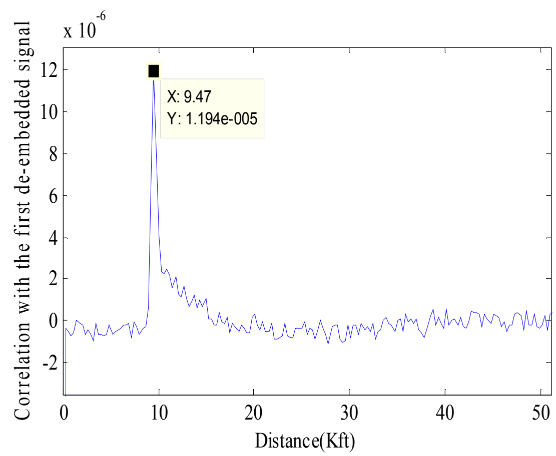

Fig.15. First de-embedded signal (W1) for test loop 3

This CTDR predicted topology is used as initial guess for the FDR optimization. The FDR signal for loop 3 is shown in Fig.16. Optimization algorithm predicts the line topology as 3.000 Kft parallel with 6.0002 Kft and the bridge tap length is estimated as 0.5Kft. For this predicted line topology, the RMS error is 7.5e-6.

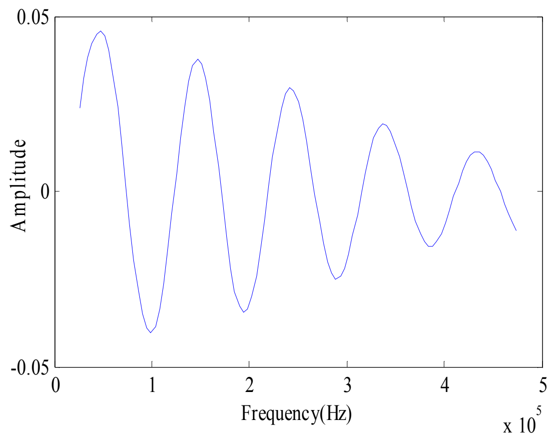

Fig.16. FDR received signal for test loop 3

Test loop 4: Fig.17 shows the variation of correlation amplitude with distance for test loop 4. A negative peak of 3.241e-6 at 9.604 Kft indicates reflection coefficient is -0.03 and this discontinuity is identified as a gauge change. A negative peak at 11.3Kft of higher magnitude (3.9e-6) indicates presence of a bridge tap at the next junction. For higher accuracy of the second segment length prediction, an auxiliary topology ($Aux^{(1)}$) of a line with gauge change at 9.6 Kft followed by infinite line is constructed. De-embedded signal is correlated with the input signal and the resultant W_1 (Fig.18) predicts a bridge tap of length 0.85 Kft at 11.19 Kft. Further de-embedding the signal locates the third discontinuity at 13.49 Kft (Fig.19).

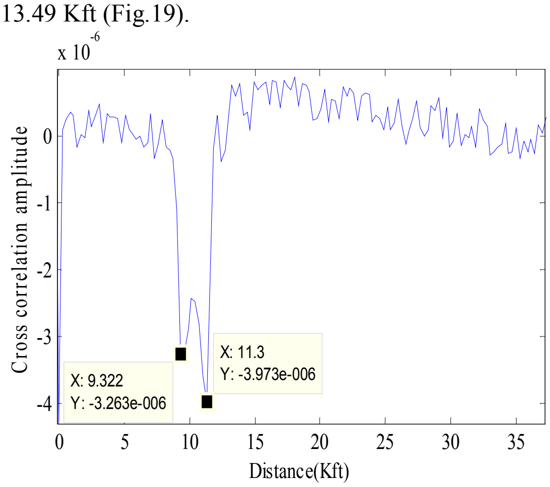

Fig.17. Distance Vs correlation amplitude for test loop 4

The FDR received signal for a test loop4, which is a line with a gauge change followed by a bridge tap is given in Fig.20. The CTDR prediction is used as a initial guess and the optimization algorithm predicts the line with a gauge change at 8.99 Kft and a bridge tap after 2.00Kft. In addition, it is predicted that third segment has an open termination at 2.00 Kft and a bridge tap at of length 0.49 Kft. As the final RMS error is 7.029e-6, this result is considered as global minimum.

The change in the first segment length has minimum impact on the error function (less reflection coefficient) compares to the impact of 2nd and 3rd line segments. This indicates that the reflected signal is sensitive to the variation of the second and third line segment lengths.

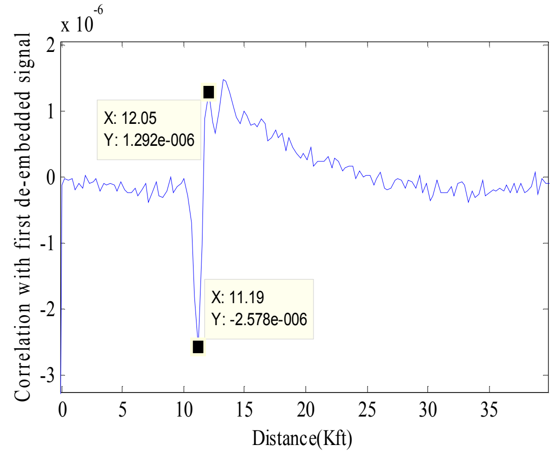

Fig. 18. First de-embedded signal (W1)for test loop 4

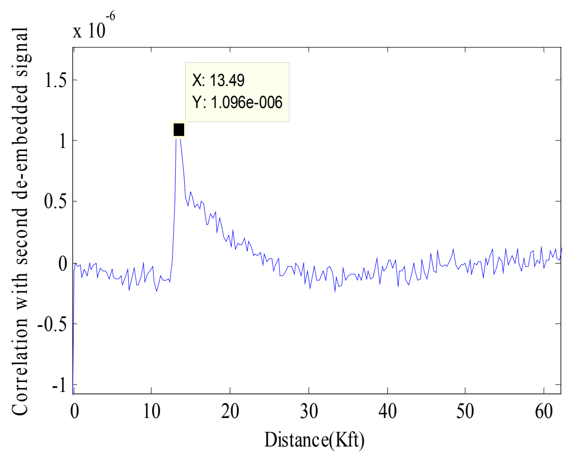

Fig.19. second de-embedded signal (W2)for test loop 4

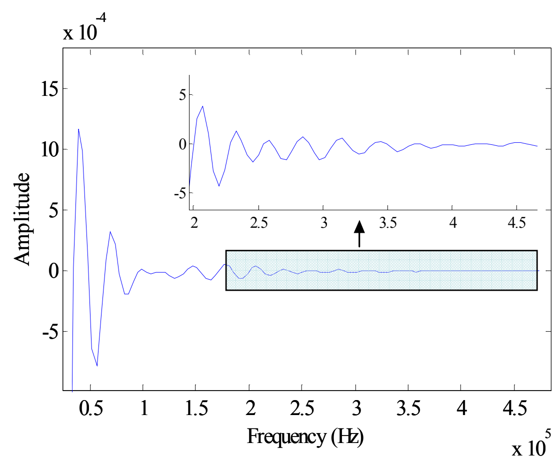

Fig.20. FDR received signal for test loop 4

Test case 5: The correlated signal amplitude for test loop 5 is shown in Fig.21. At a distance of 0.57 Kft presence of a bridge tap is estimated with the length of 0.3 Kft. Fig.22 shows W_1 after de-embedding the echo from first bridge tap. Amplitude of the second discontinuity is 2 orders lesser than the first and hence is not predictable without a perfect cancellation of the echo from the first bridge tap. Even 1% error in the estimation of the first (or) second line length leads to masking of the reflection due to the 3rd discontinuity. The second de-embedding signal W_2 does not have any significant peaks. Hence estimation of the 3rd discontinuities is not feasible using CTDR.

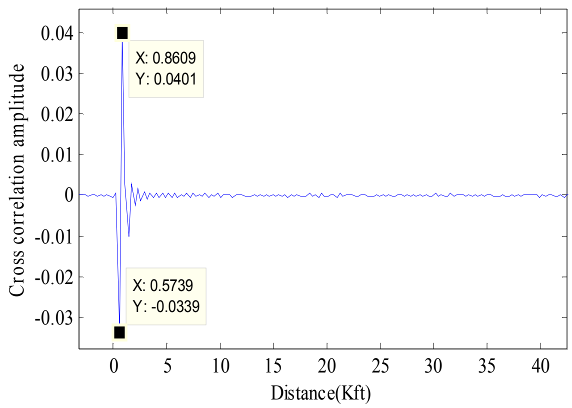

Fig.21. Distance Vs correlation amplitude for test loop 5

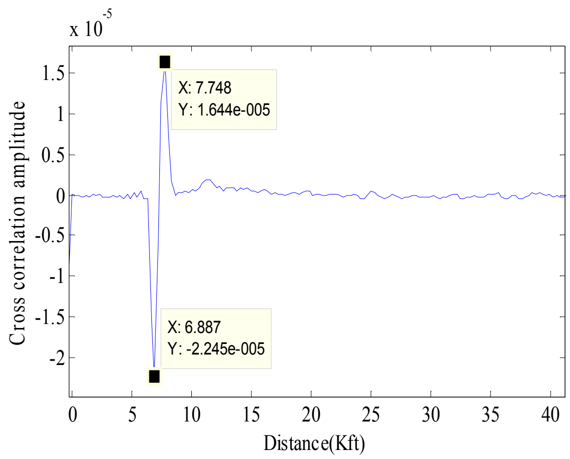

Fig.22. First de-embedded signal (W1)for test loop 5

FDR measurement for the test loop 5 shown in Fig.23 indicates that the reflection from the first bridge tap is dominant and all other reflections are masked. Further using CTDR and with de-embedding technique it is found that the line has two bridge taps but the third segment length is not predicted with CTDR. So a guess length of 2 Kft is used along with the first two predicted lengths as initial guess for the FDR analysis. FDR predicted final topology along with its RMS error is shown in Fig.24. The RMS error of the converged result is 6.5e-4. It is observed that the predicted loop is accurate for segments 1 and 2 but has about 11.5% error (3.54 Kft instead of 4 Kft) in the third segment. This is due to the very low significance of the reflection from this in the overall reflection.

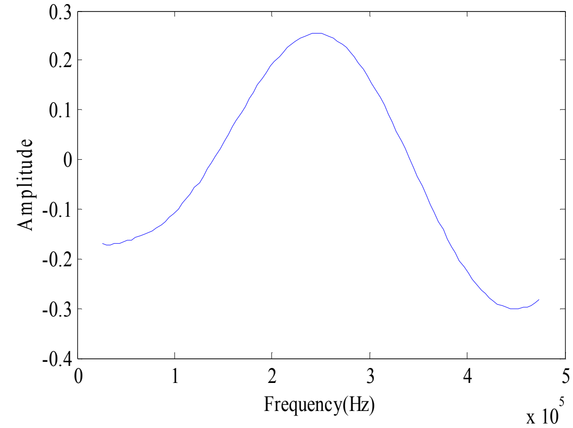

Fig.23. FDR reflected signal for test loop 5

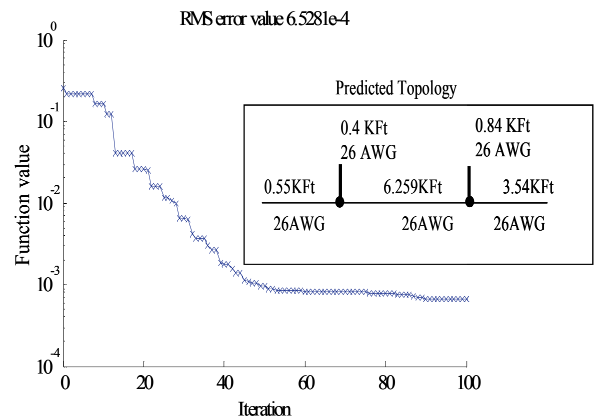

Fig.24. Convergence with the final predicted topology for test loop 5

The summary of the estimation for the defined test loops are tabulated in Table 1.

VI. Conclusion

A two step CTDR-FDR combined SELT method is developed to predict the twisted pair loop topology. In the first step CTDR measurements are used to estimate the loop discontinuities as an initial guess. This estimate is further refined using FDR based optimization method.

Results are predicted for selected ANSI test loops with this method. Loops with single discontinuities are predicted with a very good accuracy of less than 0.2 % error. For lines with more discontinuities, the prediction accuracy is good for the segments which contribute high for the reflected signal. As the method is based on matching the estimated loop reflection with the actual reflection, for the segments with lower weightage on the reflected signal, the prediction is not very accurate.

TABLE 1

ESTIMATION RESULTS USING FDR FOLLOWED BY CTDR

Test Loop	Actual loop topology (Length in Kft)	Estimated initial topology (Length in Kft)	Final Predicted Topology	Value of the Object function	% Error in the Prediction
1	12 Kft,26 AWG	12.71 Kft, 26 AWG	12.0Kft, 26 AWG	1.07e-5	-
2	9 Kft, 26 AWG – 4 Kft 24 AWG	9.32 Kft , 26 AWG – 4.51 Kft, 24 AWG	9 Kft, 26 AWG – 4 Kft 24 AWG	4.8e-6	-
3	3 Kft, 26 AWG – (0.5 Kft ,26 AWG)* – 6 Kft, 26 AWG	3.107 Kft , 26 AWG – (0.3 Kft, 26 AWG)*– 6.37Kft, 26 AWG	3 Kft, 26 AWG – (0.5 Kft ,26 AWG)* – 6 Kft, 26 AWG	7.2e-6	-
4	9 Kft, 26 AWG – 2 Kft, 24 AWG – (0.5 Kft, 26 AWG)* – 2 Kft 24 AWG	9.6Kft, 26 AWG – 1.6 Kft, 24 AWG- (0.85 Kft, 26 AWG)* – 2.3 Kft 24 AWG	8.9 Kft, 26 AWG – 2 Kft, 24 AWG – (0.49 Kft, 26 AWG)* – 2 Kft 24 AWG	6.63e-6	0.8%
5	0.55 Kft, 26AWG – (0.4 Kft, 26 AWG)* – 6.25 Kft, 26 AWG – (0.8 Kft, 26 AWG)* – 4 Kft 26 AWG	0.57 Kft 26 AWG – (0.3 Kft, 26 AWG)* - 6.31 Kft , 26 AWG (0.8610 Kft, 26 AWG)* -------	0.55 Kft, 26AWG – (0.4 Kft, 26 AWG)* – 6.259 Kft, 26 AWG – (0.84 Kft, 26 AWG)* – 3.54 Kft 26 AWG	1e-4	4.2%

* - bridge tap line segments

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