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CHARACTERIZATION OF SUBSCRIBER LOCAL LOOP BY MEASURES OF FREQUENCY RESPONSE AND TDR

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Abstract: The aim of this paper is to present procedures and methodologies in order to characterize a subscriber local loop which carries Digital Subscriber Line technology. This characterization is based on frequency response and time domain reflectometry measurements performed at local loop under test.

Keywords: Digital Subscriber Line, Local Loop Topology, Time Domain Reflectometry.

1. INTRODUCTION

The performance of a broadband access service such as Digital Subscriber Loop – DSL technology is directly related to the status of subscriber local loop [1-7]. DSL technology could provide a higher data rate than a dial-up connection access, which uses a different frequency band. However, this higher data rate depends on local loop topology. This dependency is due to the fact that the local loop was first designed to Plain Old Telephone System (POTS).

A subscriber local loop topology may contain some impairment such as gauge changes, open circuits, bridged taps along the line, and may have a long length which increases the signal attenuation. Such impairments bring about reflections on the main signal; these reflections could be weak or strong ones depending on the nature of the impairments. Furthermore, bridged taps cause strong reflections while gauge changes and open circuit causes weak ones. Additionally, it is easier to identify strong reflection than weak ones [3].

Telephone Companies which provide DSL services should have procedures or tools that characterize and evaluate the capability of a subscriber local loop in carrying DSL signals.

The capability of a subscriber local loop for DSL transmission may be evaluated by measurements and tests performed at Central Office (CO) side or at CO and customer sides simultaneously, generally referred by Single Ended Line Testing (SELT) and Double Ended Line Testing (DELT) respectively [6].

SELT technique requires only one measuring device which commonly is present at CO while DELT technique should require two measuring devices located at CO side and customer side, therefore, DELT implementation is usually more expensive than DELT one. On the other hand, DELT technique should provide a more accurate result for local loop attenuation than SELT because test pulses which are transmitted along the loop under test travel only once for DELT whereas test pulses travel twice through local subscriber loop for SELT.

The main focus of this paper is to present methodologies and procedures which could be used by a telecom operator that provides DSL services in order to characterize a subscriber local loop, that is, carried out its length and detect and locate the presence of open circuits, bridged taps and gauge changes by measurements and analysis of frequency response and time domain reflectometry (TDR) [7]. In this paper, frequency response will be performed by both SELT and DELT techniques, and then a comparison may be executed.

The present paper is organized as follows. Methods and procedures including a brief discussion about frequency response and TDR as well as lab setups, measuring device characteristics, and test loops are analyzed in Section II. Results and analysis obtained from frequency response and TDR measurements are addressed in Section III. Comparative analysis for frequency response comprising SELT, DELT, and simulated tests are showed and discussed in Section IV. Finally, conclusive remarks are drawn in Section V.

2. METHODS AND PROCEDURES

The subscriber local loop characterization will be based on Frequency Response and Time Domain Reflectometry – TDR measurements. The Frequency Response measurements consist in estimating of local loop attenuation per tone in DSL frequency band, that is, measurements that start at 4,3125 kHz and finish at 1,104 MHz for Asymmetric Digital Subscriber Line – ADSL (256 tons) and at 2,208 MHz for ADSL2+ (512 tons) [6]. The TDR measurements consist in: to send a half sine wave or a rectangular pulse with specific width along the local loop and, to analyze the reflected signal.

The analysis of such results will be used to characterize a subscriber local loop. The nature of the reflection will be perceptible at time and frequency domain, that is, every reflection caused by change of impedance along the local loop contains its signature. This signature will indicate or not presence of such impairments. The line length could be calculated by using the time of reflection knowing velocity of propagation of the pulse.

2.1. Frequency response and TDR issues

It is very intuitive that the longer a twisted pair telephone cable is, the greater the D.C. resistance. The capacitance increases with the length of the cable. Like any conductors that are wound in a spiral fashion, telephone cable also has a certain amount of inductance per unit length. When all of these factors are taken into account it can be seen that twisted pair cable has complex impedance that varies with length.

Twisted pair cable therefore has a non-linear attenuation and higher frequencies are attenuated more than lower ones. Long local loops have greater attenuation overall in frequency band as compared to short local loops, in addition, the higher frequencies on long ones are more greatly attenuated when compared to lower frequencies.

Measuring the frequency response of a local loop involves inserting a test tone of a known power level at one end and measuring the power of the tone after it passes through the loop. The difference in power level between the transmitted test tone and received test tone is the attenuation at that frequency. By stepping through a number of different frequencies, the frequency response of the loop may be determined. With the results from this test, a technician can determine if various points of loss across the specific bandwidth of interest are too great to be able to transport DSL signals. Sometimes in literature, frequency response is referred as insertion loss, attenuation, or level tracing.

In this paper, we are interested in measuring frequency response for a subscriber local loop in ADSL (1.1 MHz) frequency band. For calculating the frequency response, we are going to use the RLCG characterization based on transmission line modeling and two port network (2PN) representation. In this manner, the primary parameters (resistance, capacitance, inductance and conductance per unity of length) of a twisted pair cable are addressed in G.996 [8]. With primary parameters, we may determine the secondary parameters well known as characteristic impedance (Z_0) and propagation constant (γ). Moreover, expressing the transfer function as the ratio of the voltage on the load (Z_L) to the source (Z_S) voltage, we obtain the following relationship:

$$H(s)=\frac{V_2}{V_S}=\frac{Z_L}{Z_S\cdot(C\cdot Z_L+D)+A\cdot Z_L+B} \qquad (1)$$

Where the parameters *A*, *B*, *C*, and *D* are defined based on secondary parameters (Z_0 and γ) of a transmission line of length *d* as follows.

$$\begin{aligned} A(s)&=D(s)=\cosh(\gamma(s)d)\\ B(s)&=Z_0(s)\cdot\sinh(\gamma(s)d)\\ C(s)&=\frac{1}{Z_0(s)}\cdot\sinh(\gamma(s)d) \end{aligned} \qquad (2)$$

If twisted pair cable is open circuit terminated, frequency response is equivalent to make Z_L tends to infinity and followed result is obtained.

$$H=\lim_{Z_L\to\infty}\frac{Z_L}{Z_S\cdot(C\cdot Z_L+D)+A\cdot Z_L+B}=\frac{1}{A\cdot+Z_S\cdot C} \qquad (3)$$

From the results obtained in (1) and (3), it is possible to obtain impulse response of the local loop under test in time domain by applying inverse Fourier transform (IFFT) in *H(s)*. This approach becomes possible to calculate the total loop length identifying the travel time of the impulse.

The most general approach to evaluating the time domain response of any electromagnetic system is to solve Maxwell’s equations in the time domain. Such a procedure would take into account all the effects of the system geometry and electrical properties, including transmission line effects. However, this would be rather involved for even a simple connector and even more complicated for a structure such as a multilayer high-speed backplane. For this reason, various test and measurement methods have been used to assist the electrical engineer in analyzing signal integrity.

The most common method for evaluating a transmission line and its load has traditionally involved applying a sine wave to a system and measuring waves resulting from discontinuities on the line. From these measurements, the standing wave ratio (SWR) is calculated and used as a figure of merit for the transmission system. When the system includes several discontinuities, however, the standing wave ratio measurement fails to isolate them. In addition, when the broadband quality of a transmission system is to be determined, SWR measurements must be made at many frequencies. This method soon becomes very time consuming and tedious.

When compared to other measurement techniques, time domain reflectometry provides a more intuitive and direct look at the subscriber local loop under test characteristics. Using a step generator and an oscilloscope, a fast edge is launched into the transmission line under investigation. The incident and reflected voltage waves are monitored by the oscilloscope at a particular point on the line.

This echo technique reveals at a glance the characteristic impedance of the line, and it shows both the position and the nature (resistive, inductive, or capacitive) of each discontinuity along the line. TDR also demonstrates whether losses in a transmission system are series losses (open and short circuits) or shunt losses (presence of bridged tap). All of this information is immediately available from the oscilloscope’s display.

To simulate this technique, the IFFT of the following relation, defined in frequency domain, should provide the wave form in time domain when a voltage (V_S) is applied in the input port of subscriber local loop. If voltage source is a square pulse, we obtain the pulse response of the line.

$$V_1=\frac{Z_{in}}{Z_{in}+Z_S}\cdot V_S \qquad (4)$$

Where Z_{in} is the input impedance of local loop defined as follows.

$$Z_{in} = \frac{Z_L A + B}{Z_L C + D} \tag{5}$$

In this paper we interested in calculate the total loop length, detect and locate impairment such as bridged tap and gauge changes. First, to calculate the total loop length (l), we are going to analyze the wave form of TDR trace and investigate travel time of pulse (t_1). The following relation should calculate the total loop length:

$$l = \frac{t_1}{2} \cdot VOP \tag{6}$$

Where VOP is the velocity of propagation of the pulse (66% of c [7]) in twisted pair cable.

For loop with one bridged tap and formed by only one kind of cable (same gauge in overall loop), TDR trace should provide an accurate bridged tap location ($BT_{Location}$) and bridged tap length (BT_{Length}) as follows:

$$BT_{Location} = \frac{t_2}{2} \cdot VOP \tag{7}$$

$$BT_{Lenght} = \frac{t_3 - t_2}{2} \cdot VOP \tag{8}$$

Where t_2 is the time propagation of pulse reflection caused by presence of bridged tap and t_3 is the time propagation of the pulse caused by open circuit termination of the bridged tap.

Gauge change is a more complex problem because this kind of discontinuity causes very weak reflections which are sometimes mixture with other reflections or even completely attenuated by the local loop nature. TDR technique is more capable to detect this weak reflection if it was generated by a near discontinuity. In [3] is presented a technique which becomes reliable the detection of the first gauge change and in [4] and [5] are presented the extension of this technique to detect all gauge changes present in the subscriber local loop.

To detect gauge change from TDR trace, equation (6) may be used also.

2.2. System configuration

To obtain faster results, an automated environment has been implemented to perform SELT and DELT. It consists in one measuring device for SELT and two measuring devices for DELT, the local loop under test, and a computer. The measuring device performs frequency response and TDR tests in the local loop. This local loop is a pair of telephone copper cable which may contain open circuits, gauge changes, and bridged taps. The computer which is connected to Internet performs the measuring device configurations, store the results, define the nature of the test (frequency response, TDR, DMT, etc) and its complete control, that is, the measuring device will be controlled and set up by the computer. Figure 1 and 2 summarizes the measurement environment for SELT and DELT, respectively, with the loop under test connected to measuring device.

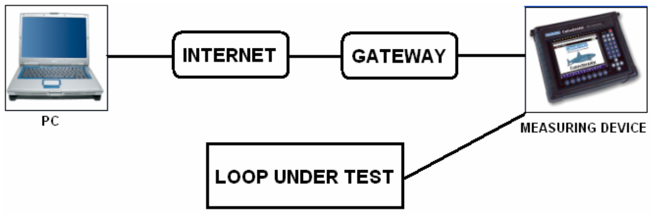

Fig. 1. Measurement environment (Setup 1 – SELT)

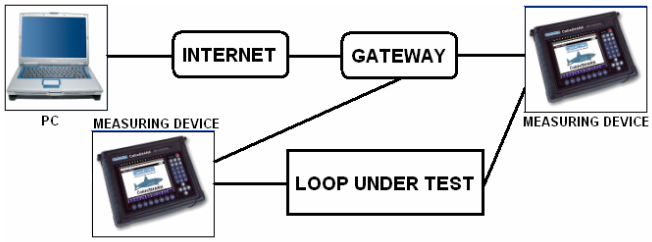

Fig. 2. Measurement environment (Setup 2 – DELT)

2.3. Measuring device characteristics

The Measuring Device is a cable qualifier, Cable Shark P3, which could fulfill some tests in order to determine some characteristics of the subscriber local loop. The transmitter frequency band starts at 300 Hz and ends at 2,2 MHz with accuracy of ± 0.3 Hz using a source impedance of 100 Ω. The receiver frequency band is the same of the transmitter however it has a worse accuracy of ± 2 Hz [9].

For the paper purpose, just frequency response and TDR tests will be carried out, nevertheless it is worth pointing out that the measuring device is able to perform other tests such as Discrete Multi Tone – DMT, Frequency Domain Reflectometry – FDR and son on. Thus, the main contributions of the present work include methodologies for determining length of cables and bridged tap detection from frequency responses and TDR tests.

2.4. Test Loops

The subscriber test loops are Loop 1 and Loop 2 as could be seem in figures 3 and 4. Loop 1 is formed by two sections, first one with 1 km and 0.40 mm gauge and second one with 1 km and 0.50 mm gauge, in this cause, we interested in predict the gauge change locate at 1 km and calculate its total length. Loop 2 is formed by one section with 2 km and 0.40 mm gauge and a 500 m bridged tap (0.40 mm) addressed in center of the loop, thus we object detect the presence of such bridged tap and calculate its location and length.

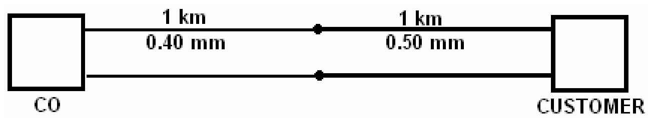

Fig. 3. Measurement environment

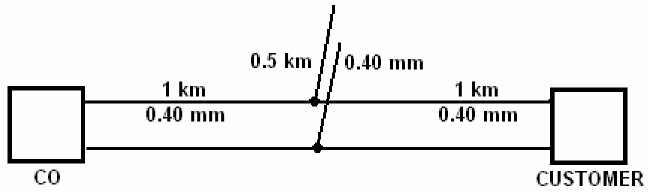

Fig. 4. Measurement environment

3. RESULTS AND ANALYSIS

This section presents the results obtained from frequency response (SELT) and time domain reflectometry test carried out for subscriber loops 1 and 2 as shown in figures 3 and 4.

3.1 Loop 1

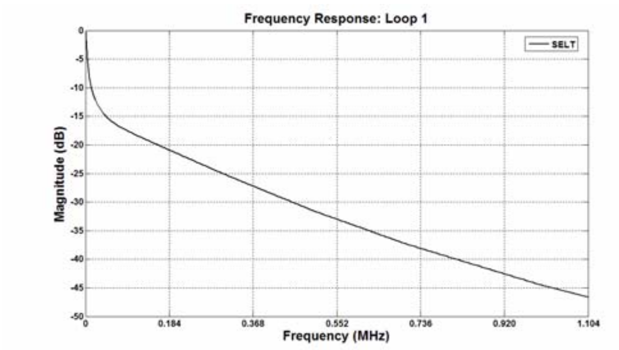

Fig. 5. Frequency response for Loop 1 (SELT)

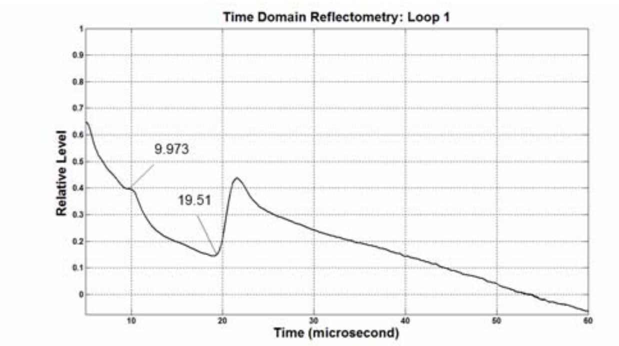

Fig. 6. Time Domain Reflectometry for Loop 1

From frequency response result for loop 1 shown in figure 5, we may see that attenuation per tone in ADSL frequency band shows a linear fashion with no reflection present, this way, frequency response have not been able to detect the change of gauge. However, inspect the TDR trace shown in figure 6 we may see the reflection caused by the gauge change and the reflection caused by open circuit terminated of twisted pair. This way, making use of (6), we may calculate the presence of the gauge change in 997 m (t_1 = 9.973 µs) and calculate the total loop length of 1951 m (t_1 = 10.51 µs).

3.2 Loop 2

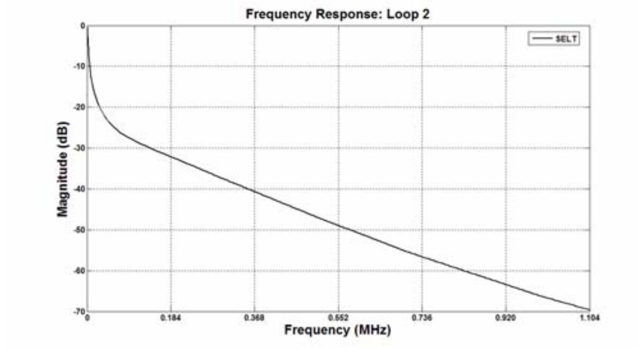

Fig. 7. Frequency response for Loop 2 (SELT)

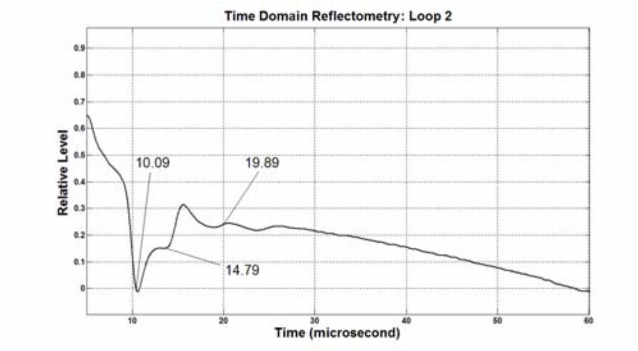

Fig. 8. Time Domain Reflectometry for Loop 2

From frequency response result for loop 2 given in figure 7, obtained using only one measuring device (SELT), we may see that attenuation per tone in ADSL frequency band shows a linear fashion with no reflection present caused by the presence of bridged tap in center of the loop, this way, frequency response have not been able to detect strong reflection in SELT tests. It is worth emphasizing that the IFFT of this result should not give these reflections either. Nevertheless, inspect the TDR trace shown in figure 8 we may see the reflections caused by the presence of bridged tap and its open circuit terminated. It is also possible to see reflection from the end of the loop. This way, making use of (7) and (8), we may calculate the location of the bridged tap in 1.009 km (t_2=10.09 µs) and calculate the bridged tap length of 470 m ($t_3 - t_2$ = 4.7 µs). The reflection seem in 19.89 µs is generated by the end of loop, thus the total loop carried out by (6) is 1989 m.

4. COMPARATIVE ANALYSIS

This section presents the results obtained from frequency response measurements using SELT and DELT techniques as well as the frequency response carried out by simulation tools discussed previously. In figure 9 is given the result for loop 1 whereas figure 10 has the result for loop 2.

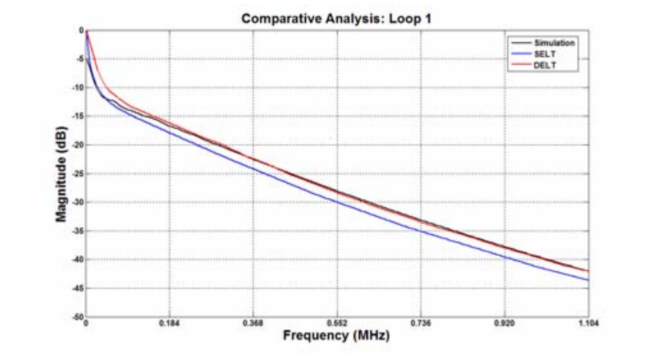

Fig. 9. Frequency response for Loop 1 (SELT, DELT, and Simulation)

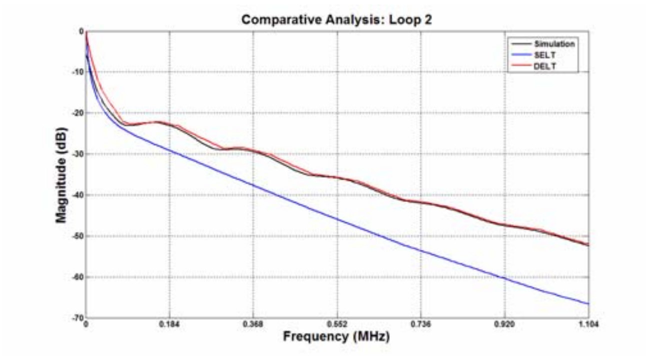

Fig. 10. Frequency response for Loop 2 (SELT, DELT, and Simulation)

From the results above, we may see that the frequency response obtained from two measuring device (DELT technique) approach to simulated result more than curve obtained from SELT technique. The difference between DELT curve and SELT curve was about 2 dB. The reason for that result is: SELT measurement is performed with infinity load impedance whereas DELT measurement uses the load impedance of the measuring device (600 Ω). As we may see in (1), the frequency response is directly dependent of the load impedance. The IFFT of the result above should give the total loop length of about 2 km, but not detect the presence of the gauge change locate in the center of the loop.

Figure 10 shows the result for loop 2, and as already been discussed, DELT technique exhibit the curve, for frequency response, more approach and similar fashion to simulation curve than SELT technique. With DELT curve, we may see the oscillations caused by the presence of the bridged tap (strong reflection), and from such result it is possible to get the frequency of the first null (about 86 kHz) [2] and calculate the bridged tap length while in SELT curve the oscillations are not seen. It is worth pointing out that the IFFT of DELT curve should provide the impulse response, then reflections from the bridged tap location, from the end of the bridged tap, and from the end of the loop will be clearer as shown in TDR trace.

From the results above, we may see that frequency response obtained from double ended line testing (DELT) should provide a more accurate result than single ended line testing (SELT). The reasons are related to test tone transmitted by the measuring device through the loop as already been discussed in previous sections.

5. CONCLUSION

The enormous impact of the Internet in everyday life and the Telecommunications Act of 1996 opened up the global market for broadband data access. Today several types of Digital Subscriber Line (DSL) technologies are rapidly becoming standards for delivering this access on copper access network cables to the end user.

In the competition of the available market for offering end users with new services like xDSL, operators face a number of challenges. These result from the fact that the cable network has a unique topology per user depending on type of cable, length of cable, taps and such.

In order to offer the end user xDSL services in a cost efficient way, the operator needs to be able to pre-qualify the loop. At the initial stage of deployment the operators used to send out technicians both to the end user and the Central Office (CO) to pre-qualify the loop. This is a very costly exercise.

The quality of DSL service is directly dependent on the status of subscriber local loop which was the goal of this paper. Therefore, this paper gives methods and procedures to calculate the total loop length with a desirable accuracy, about 3%, detect the presence and locate bridged tap as well as bridged tap length determination. It is worth pointing out that bridged taps presence in subscriber local loop cause several injuries to the main signal which may cause bit errors in DSL transmission. For this reason, this impairment was most discussed in this paper.

Next step of this research is applying paper purpose to more complex loops, for example, to loops with more than one discontinuity, mixture of gauge, and more than one bridged tap and extended it to other kind of test like FDR, DMT, and so on.

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