Standards Project: VDSL

Title: Effect of Bridged Taps at VDSL Frequencies

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Abstract

This contribution presents a study of the effects of bridged taps on VDSL transmission systems. Specifically, it is shown that the short bridged taps, which affect VDSL signals, are much more damaging than the longer bridged taps, which affect other xDSL signals, such as HDSL and ADSL. It is recommended that this issue be addressed in the VDSL system requirements document.

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1. INTRODUCTION AND SUMMARY

Practicing engineers involved in the development of HDSL and ADSL transceivers know that bridged are somewhat of a nuisance, but can, generally, be handled by properly designing the HDSL/ADSL transceivers. However, the same is not true for the VDSL application. The reason is that the VDSL signals are affected by much shorter bridged taps than other xDSL signals, which use much lower frequencies. As will be shown here, the short bridged taps introduce much less loss in the reflected signals than the longer bridged taps, even though the frequencies involved are much higher. As a result, the “nulls” introduced by the short bridged taps are much deeper and wider. In addition, the overall propagation loss introduced by multiple bridged taps can quickly become unmanageable at VDSL frequencies when the number of bridged taps is increased. For example, certain combinations of three bridged taps with lengths in the 10’ to 100’ range can introduce an additional overall propagation loss that is close to 30 dB. This is much more loss than would be introduced if the three bridged taps were cascaded with the active portion of the loop.

The rest of the contribution is organized as follows. The effect of so-called quarter-wavelength bridged taps is discussed in the next section. An engineering rule that can be used to predict the frequencies of the nulls introduced by bridged taps is derived in Section 3. The depth of the nulls is discussed in Section 4. Finally, a brief discussion of the transfer function of loops with bridged taps is given in Section 5.

2. EFFECT OF BRIDGED TAPS

A bridged tap is an open-ended twisted pair, which is connected in shunt with a working loop, as shown in Fig. 1. At the bridging location (point B in the figure), the signal transmitted by the signal generator on the left is split into two components. The component that propagates on the bridged tap is reflected back at the other end of the bridged tap and is then recombined at point B with the signal propagating on the working portion of the loop.

Assume now that the length of the bridged tap is d and that the signal generator on the left in the figure transmits a sinewave with frequency f. This electrical signal has some wavelength l on the loop. When the length of the bridged tap is equal to one quarter of the wavelength, i.e. $d = l/4$, the signal on the bridged tap propagates over a distance $2d = l/2$. As a result, at point B the reflected signal is 180° out of phase with the signal arriving on the working portion of the loop and partially cancels this signal. This produces a so-called “null” in the transfer function of the communication link between points A and C in the figure. The location of these nulls on the frequency axis is discussed next.

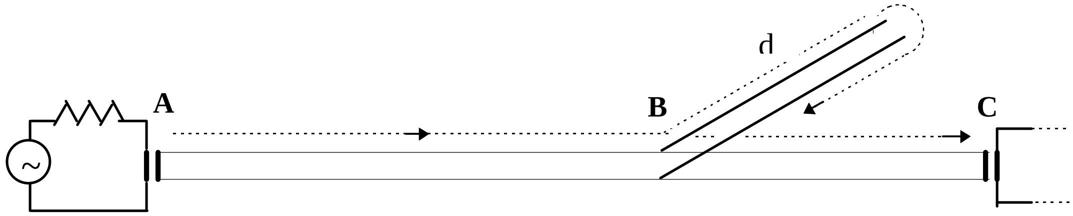

Figure 1 - Active Loop with One Bridged Tap

3. LOCATION OF THE "NULLS" INTRODUCED BY BRIDGED TAPS

The analysis presented in this section is not completely rigorous, but leads to an engineering rule, which has proved to be quite accurate and useful in practice. We now make the following definitions:

- d = length of bridged tap
- c = velocity of light in vacuum = 299,792. 5 km/s = 983,619.2 kft/s
- v = velocity of electrical signal on loop at frequency f
- l = wavelength corresponding to velocity v and frequency f
- e_r = relative dielectric constant of the loop's insulation

With these definitions, we have the following well-known relationships:

$$l = \frac{v}{f} \qquad\qquad v = \frac{c}{\sqrt{e_r}} \tag{1}$$

Consider now the case where the frequency f is equal to some value f_o for which the length of the bridged tap is equal to one quarter of the wavelength. Using (1) we then have:

$$d = \frac{l}{4} \qquad \rightarrow \qquad f_o = \frac{v}{4d} = \frac{c}{4d\sqrt{e_r}} = \frac{K}{d} \tag{2}$$

Thus, the location of the first null introduced by the bridged tap is simply inversely proportional to the length d of the bridged tap and is a function of the insulation used for the twisted pair. Additional nulls are introduced at frequencies for which the length of the bridged tap is equal to odd multiples of the quarter of the wavelength, i.e. $d = (2n+1)\,l/4$, where n is a positive integer.

The following table gives some typical values for the dielectric constant e_r of commonly used types of insulation for unshielded twisted pairs.

Typical values for the relative dielectric constant e_r			
Frequency	1 kHz	1 MHz	100 MHz
Polyethylene	2.25	2.25	2.25
Polyvinyl chloride (PVC)	3.1	2.9	2.8
Pulp (paper)	3.3	3.0	2.8

Notice that e_r is constant with frequency for polyethylene, but not for PVC and pulp. Specializing (2) to polyethylene we get the following easy-to-remember formula:

$$f_o = \frac{50}{d_m} = \frac{164}{d_{ft}} \tag{3}$$

where f_o is expressed in MHz, d_m is the length of the bridged tap expressed in meters, and d_{ft} is the same length expressed in feet. Because the dielectric constant of polyethylene does not vary with frequency, the transfer function of the loop with bridged tap will also have nulls at frequencies which are close to odd multiples of the frequency in (3), i.e. at frequencies $(2n+1)\, f_o$. The exact location of the nulls can be found by using the results given in Section 5. These results were used to compute the transfer function of the loop configuration shown in Fig. 2 for bridged tap lengths of 300', 200', and 100'. The three transfer functions are shown in Fig. 3. The cable characteristics used in the computations were those of the TP2 cable described in [1].

4. DEPTH OF THE NULLS INTRODUCED BY BRIDGED TAPS

The sinewave propagating on the bridged tap travels over a distance *2d*. The magnitude of the transfer function of such a twisted-pair channel can be expressed as:

$$|H_{bt}(f)| = e^{-2da(f)} \approx e^{-2da\sqrt{f}} \tag{4}$$

where *a(f)* is the twisted pair's attenuation constant, and the approximation on the right assumes that *a(f)* varies as the square root of frequency. This is a good approximation for cables using polyethylene or pulp insulation, but does not hold for PVC. Using (2) in (4) we get for the first null:

$$|H_{bt}(f_o)| = e^{-\frac{2Ka}{\sqrt{f_o}}} \rightarrow 1 \quad as \quad f_o \rightarrow \infty \tag{5}$$

Notice that the transfer function approaches unity when f_o becomes very large, or, equivalently, when the length of the bridged tap becomes very small. Thus, the loss experienced by the sinewave propagating on the bridged tap decreases when the frequency of the first null increases, and cancellation of the incoming signal at point B in Fig. 1 becomes more severe. This results in first nulls which are much deeper at higher frequencies than at lower frequencies, as illustrated in Fig. 4. The transfer functions shown in this figure were obtained with the loop arrangement shown in Fig. 2.

The five different transfer functions correspond to the following bridged tap lengths:

d = 320', 80', 32', 16', 8'

Only the first null introduced by a given bridged tap is shown in the figure. The other nulls are not shown. This was done to simplify the figure. Notice that the depth of the nulls increases when the length of the bridged tap decreases, as predicted by the previous analysis. In addition, the width of the nulls also increases.

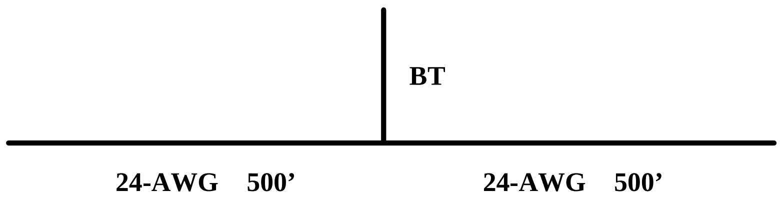

Figure 2 - Loop Configuration with Bridged Tap

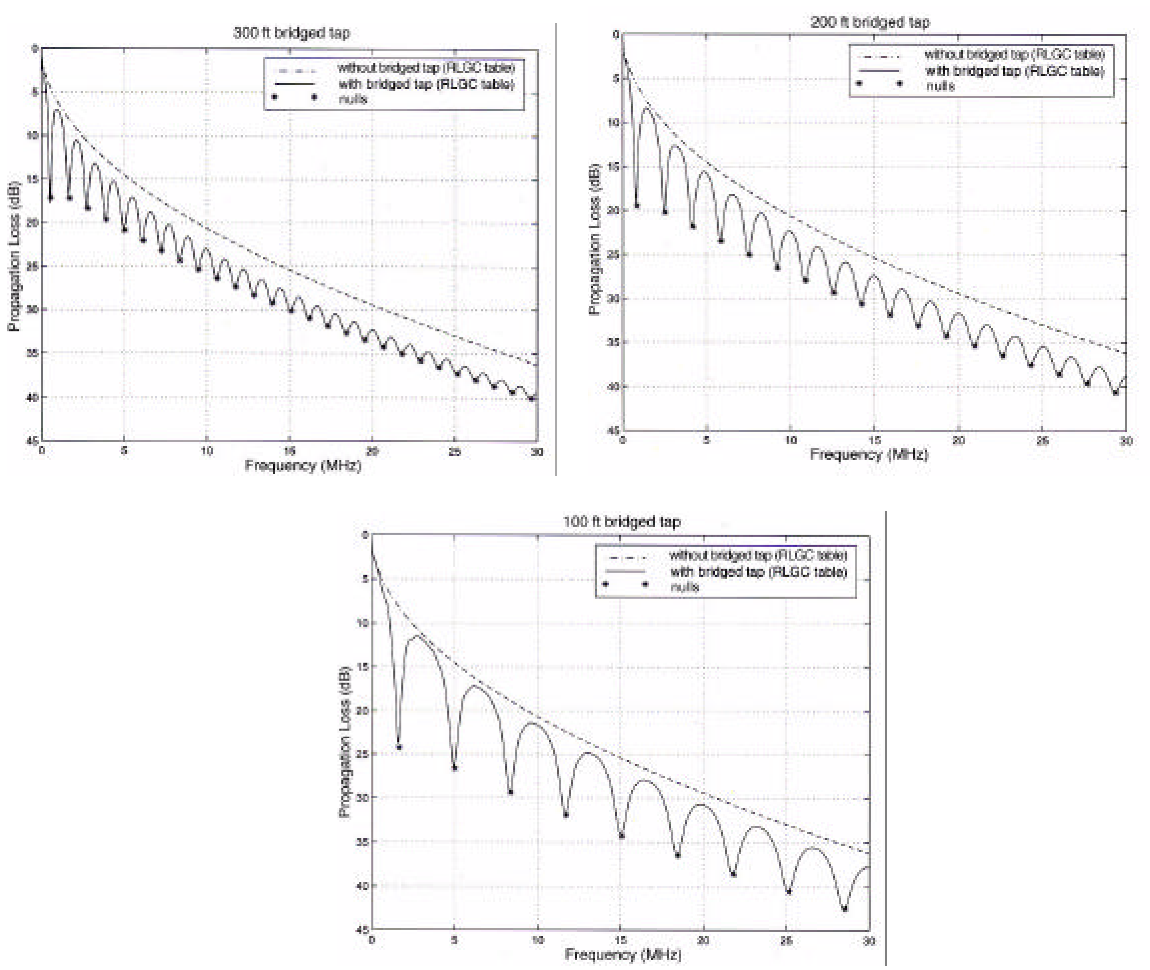

Figure 3 - Transfer Function of Loop for Various Bridged Tap Lengths

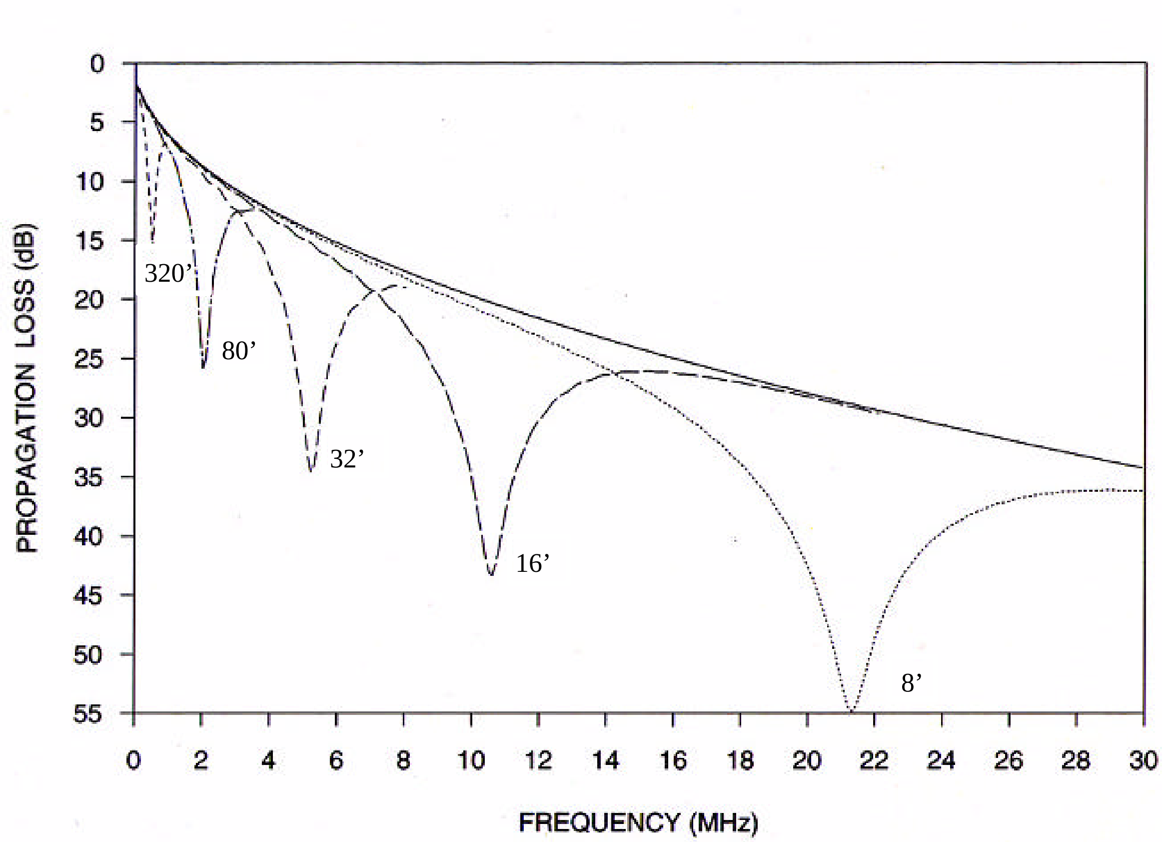

Figure 4 - First Null Introduced by Bridged Taps with Various Lengths

It should be apparent from Figs. 3 and 4 that short bridged taps introduce a lot of linear distortion in the loop’s transfer function. In addition, they also tend to introduce more overall propagation loss than longer bridged taps. It can be shown, for example, that certain combinations of three bridged taps with lengths in the 10’ to 100’ range can introduce as much as 30 dB of additional propagation loss in the VDSL frequency band. (This is much more loss than what would be obtained if the bridged taps were cascaded with the working portion of the loop.) In contrast, for the HDSL/ADSL frequency band, the worst-case propagation loss introduced by three bridged taps is more likely to be in the 10 dB range.

5. TRANSFER FUNCTION OF LOOPS WITH BRIDGED TAPS

For completeness, we provide here the exact expression for the loop configuration with bridged tap that is shown in Fig. 5. In this figure, Z_{0i} and d_i represent the characteristic impedance and length of loop segment i, where i = 1,2,3.

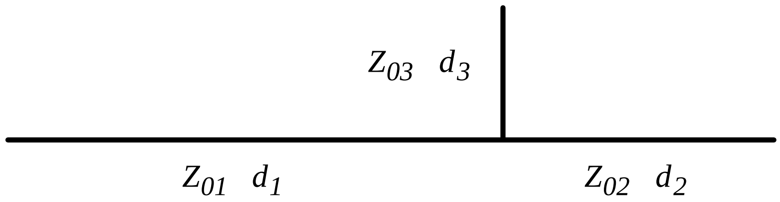

Figure 5 - Loop Configuration with Bridged Tap

The transfer function of this loop is given by Eq. 22 in [2] for the case where the active portion of the loop is perfectly terminated. This equation is repeated here:

$$H(f) = \frac{Z_{02}}{Z_{01} + Z_{02} + (Z_{01} Z_{02}) Z_{bt}^{-1}} e^{-g_1 d_1} e^{-g_2 d_2} \tag{6}$$

where

$$Z_{bt} = Z_{03} \frac{cosh(g_3 d_3)}{sinh(g_3 d_3)} \tag{7}$$

is the input impedance of the bridged tap and g_i is the propagation constant of section *i*. This constant can be computed from

$$g(w) = \sqrt{(R + jwL)(G + jwC)} \tag{8}$$

where *R, L, G,* and *C* are the primary constants of the cable section and $w = 2pf$.

It is easily verified that the location of the bridged tap does not affect the transfer function in (6) when the total length of the working portion of the loop is kept constant and the electrical characteristics of sections 1 and 2 are the same, i.e. $g_1 = g_2$. Also, at frequencies for which the length of the bridged tap is very large compared to the wavelength, we have $Z_{bt} \approx Z_{03}$ in (7). Using this result in (6) and assuming that all the sections of the loop have the same characteristic impedance we find that electrically long bridged taps introduce a flat attenuation equal to 3/2 or about 3.5 dB. Notice on the top left in Fig. 3 that this is the amount of flat loss that is obtained with a 300' bridged tap at frequencies close to 30 MHz.

6. REFERENCES

[1] "Very-high-speed Digital Subscriber Lines," System Requirements, ANSI T1E1.4, 1997.

[2] Jean-Jacques Werner, "The HDSL Environment," *IEEE J-SAC*