

RADIO FREQUENCY INTERFERENCE AND CAPACITY REDUCTION IN DSL

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ABSTRACT

The issue of radio frequency interference in Digital Subscriber Line (DSL) networks is of particular concern in urban areas with many strong radio sources nearby. This paper investigates in detail the mechanisms underlying the capacity reduction due to the presence of radio frequency signals from Amplitude Modulated (AM) broadcast stations in an ADSL network. An ADSL system, channel, and radio frequency interference noise were simulated in MATLAB. The capacity reduction due to different Radio Frequency (RF) ingress conditions was studied. Spectral Spreading of the RF interferer, as suggested by Harris *et al* [1], is a primary cause of capacity reduction, but only at long loop lengths where the signal to Gaussian noise ratio is very low.

KEY WORDS

DSL, RF Interference, Broadband.

1. INTRODUCTION

To address the need for high data rates in the “last mile”, broadband access technologies like Digital Subscriber Line (DSL) and cable modem were introduced. DSL provides data rates on the order of Mbps. These theoretical maximum rates can be achieved only under ideal conditions. The actual data rates achieved depend on the channel characteristics and noise conditions in the channel. Noise can be in the form of crosstalk noise from other twisted pairs in the same bundle, or it can be noise from sources which are external to the bundle. A powerful external source may induce noise in the DSL line. In urban areas where DSL is widely deployed, there are many Radio Frequency (RF) sources. These RF signals may couple to the DSL link.

The Amplitude Modulated (AM) Medium Wave (MW) broadcast band in the United States is 550 kHz – 1700 kHz. A portion of this band overlaps with the full rate Asymmetric Digital Subscriber Line (ADSL) downstream band. The radio frequency signals transmitted by AM

broadcast stations couple onto the DSL line through both aerial and buried telephone wire, and the coupling is accentuated by poor balance of cable and unterminated lines.

The paper by Harris *et al* [1], which was the motivation for this work, states that uniform data windowing in G.lite ADSL systems could be the reason for capacity reduction as uniform windowing causes spectral spreading of RF signals. However, their model does not have an equalizer in its receiver because the motivation for G.lite was to reduce complexity of the modem wherever possible. In contrast with industry practice, when Harris’s work first appeared, most ADSL modems now include an equalizer even though an equalizer is not mandated by the standard. Since ANSI and G.dmt ADSL systems are widely deployed compared to G.lite systems, the capacity reduction in an ANSI ADSL system due to radio frequency interference was studied in this work. AM transmitters are considered as RF noise sources in this study. The results of this study can be extended to any xDSL system which uses the DMT modulation technique.

2. AM RADIO INTERFERENCE

Radio frequency sources such as amateur (Ham) radios, AM broadcast stations, and RF heating systems operate in the xDSL frequency spectrum and may cause interference problems if the RF noise enters the DSL line. Ham radio signals are unpredictable and may appear and disappear at any frequency within the bands allocated to Hams at any time. The induced Ham radio and AM broadcast signals in the DSL line may be very strong when compared to DSL signals in the twisted pair wire.

Double Side Band AM (DSB-AM) broadcast signals are 10 kHz wide. The strength of an AM interference signal on the DSL link depends on the location of the AM ingress source, direction of the source, and strength of the transmitted signal. Harris *et al* [1] measured the highest RF disturbance strength in the local loops of two Canadian cities, which had a distribution of 60% aerial plant and 40% buried plant. Their results show that the median interference level of the differential mode RF ingress signal was –53 dBm and 10% of the homes

experienced interference of -37dBm or higher [1]. The RF ingress level in a buried plant is only 4 dB below the aerial plant ingress levels [2]. Harris's [2] paper shows that the interference signal may be as strong as the DSL signal at the tones where the AM ingress signal's spectrum overlaps with the DSL signal.

The radio frequency interference will affect the front end of the ADSL system. There are possibly non-linear and linear effects which may be caused by RFI. These effects may reduce the link capacity.

Non-linear effects

- 1) The common mode rejection ratio of the front-end amplifier determines the extent to which the common mode signal is cancelled. Inadequate cancellation of the common mode signal may reduce the effective dynamic range of the analog to digital converter, and may cause a decrease in the overall Signal to Noise Ratio (SNR) by activating the automatic gain control.
- 2) Intermodulation products in the band of ADSL may appear in the front-end amplifier.

Linear effects

- 1) Implicit rectangular windowing in DFT demodulation causes spectral spreading of the narrow band interferer.
- 2) Direct interference to tones within bandwidth of interferer.

Only linear impairments are studied in this work. The following issues are analyzed in this study:

- 1) The role of a time domain equalizer in RFI cancellation.
- 2) The issue of rectangular windowing versus non-uniform windowing.
- 3) RFI cancellation using a bandstop filter.

3. SIMULATION MODEL

Figure 1 shows the block diagram of the ADSL system simulated for this study. An ATU-C transmitter and ATU-R receiver are modeled. The model was simulated in MATLAB ver. 6.1. The constellation point for each tone is randomly generated and modulated using IFFT. A cyclic prefix is added to each DMT symbol. The channel is simulated using an approximate model which represents a 0.5 mile (2640 feet) long 26 gauge twisted pair wire given by equation 1 [3].

$$H(d, f) = e^{-d(k_1\sqrt{f} + k_2f)} e^{-jdk_3f}, \quad (1)$$

where d is distance in miles,
 f is frequency in Hertz,

and for 26 gauge twisted pair copper wire the values of the constants k_1, k_2, k_3 are,

$$k_1 = 4.8 * 10^{-3}$$

$$k_2 = -1.709 * 10^{-8}$$

$$k_3 = 4.907 * 10^{-5}$$

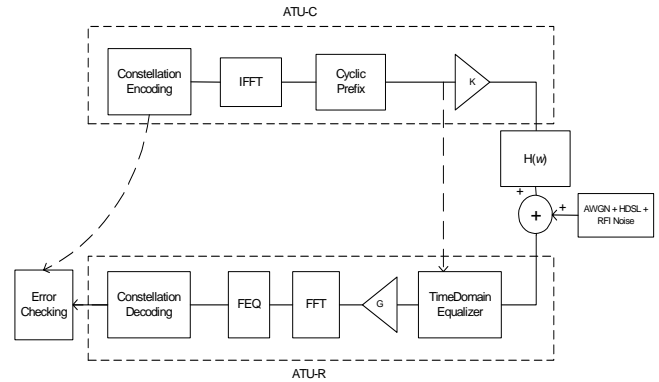


Figure 1: Simulation Model Block Diagram

The DMT signal is convolved with the channel impulse response, and white Gaussian noise, HDSL crosstalk noise, and AM broadcast interference are added. At the receiver, the signal is equalized and the equalizer coefficients are calculated when the $G.hs$ training signals are transmitted. The Time Domain Equalizer (TEQ) is simulated using a 32-tap block adaptive Wiener FIR filter. After time domain equalization, the cyclic prefix is removed and the data is demodulated. The Frequency Domain Equalizer (FEQ) performs minor correction of phase and amplitude errors at each tone. For each tone the correction factor is the inverse of the composite frequency response of all filters through which the signal passes (the channel and TEQ in this simulation). The FEQ equalized data is then decoded. A constant bit allocation of 4 bits per tone is assumed.

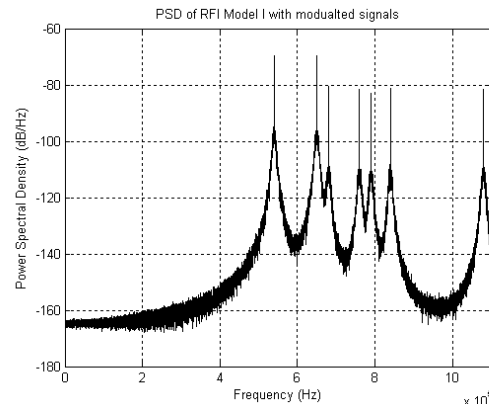


Figure 2: Simulated Modulated G.test RFI model I

Two noise cases, a single ingress source and multiple ingress sources, are taken into consideration. The first case is an AM broadcast station operating at 540 kHz as the source of ingress noise. The second case is where the RFI Model I in G.test [4] is modified. As an extension of the G.test RFI models, modulated AM signals with the defined carrier frequencies and power levels are generated. In both cases only the RFI components inside the ANSI-ADSL band are considered. The power spectral density of simulated modulated G.test RFI Model I ingress signal is shown in Figure 2.

Capacity Reduction Metric

The capacity reduction is studied with two metrics: (1) the Euclidean distance between the transmitted constellation point and the received constellation point for each tone, and (2) the number of tones in error. The Euclidean distance method gives a better understanding of the magnitude of error. This distance is the length of the error vector in signal space. If the error vector is larger, then the probability for the tone to be decoded incorrectly is greater. If the error vector is small, then the data may be accurately recovered with error correction methods.

For the second metric, a tone is decided to be in error if the received signal is decoded to be a constellation point which is different from the transmitted constellation point. The Euclidean distance between the recovered data point and all possible constellation points is calculated. The received data is decoded as the constellation point which has the shortest distance to the received data point. Error checking is not done in terms of bits in error, as no error checking and error correction features are embedded in this simulation.

Simulation Scenarios

The following simulation scenarios are used in this study.

1) Baseline Model

An Interference Free Channel is the baseline case. The channel response model is used and White Gaussian Noise (AWGN) of -140 dBm/Hz is added to the channel. All remaining cases add impairments to this baseline case.

2) Single Ingress Source

2a) RFI Plus Crosstalk: In this case the channel has AWGN, 24-disturber HDSL crosstalk noise, and radio frequency interference (AM broadcast station at 540 kHz).

2b) Bandstop Filter Preprocessing: This test case is similar to case 2a, but the RFI is cancelled with a 10 kHz bandstop filter. A 2nd order 10 kHz (535 kHz – 545 kHz) stopband Butterworth filter precedes the equalizer.

3) Multiple Ingress Source

Modulated G.test RFI Model I: This case is similar to case 2, but the RF ingress signal is the modulated G.test RFI Model I.

The following assumptions were made in the simulations.

- 50 randomly generated DMT data symbols are transmitted.
- The transmitted signal has a total average power of +17 dBm in the downstream direction.
- RFI signal total average power is -40 dBm.
- Loop length = 0.5 miles (2640 feet).

- Tones 32 to 255 (except tone 64) carry data in downstream direction (233 data bearing tones in total).
- Average, maximum and minimum number of tones in error are calculated for the 50 symbol set.
- For error calculation, the first symbol is neglected as there is no ISI effect in that symbol.
- All signals are bandlimited to 1.104 MHz.

4. SIMULATION RESULTS

Case 1: Interference Free Channel

Figures 3 and 4 show the TEQ frequency response and average error vector magnitude for this case. The average number of tones in error is 4.96 tones (2.13 % of the tones).

Case 2: Single Ingress Source

Case 2a: RFI Plus Crosstalk

Figures 5 and 6 show the TEQ frequency response and average error vector magnitude for this case. From the equalizer response it can be seen that the equalizer is trying to cancel the RF ingress noise. The equalizer does not do a perfect job in canceling the RFI. From the average error vector magnitude plot it can be seen that the tones near 540 kHz are affected. The average number of tones in error per DMT symbol is 9.43 tones (4.05 %).

The paper by Harris *et al* suggests that the capacity decrease is due to spectral spreading of interferer energy as a result of rectangular windowing [1]. From Figure 6 it can be seen that the capacity decrease at this loop length is mainly due to the direct effect of AM ingress noise on the tones in the interferer's bandwidth rather than spectral spreading to other tones. To investigate this further, an ADSL signal was transmitted across an ideal channel in the presence of AWGN alone and with sinusoidal ingress noise source at 540 kHz alone. Figures 7 and 8 show the average error vector for these cases in log scale. The windowing effect is seen in the broadening of the interferer's spectral line in Figure 7. The comparison threshold for this spectral spreading is the AWGN noise case (Figure 8). Note that the error vector "floor" for the sinusoidal interferer is about 7dB above the error vector floor in the AWGN case. This will vary with interferer strength of course

Case 2b: Bandstop Filter Preprocessing

Figures 9 and 10 show the TEQ frequency response and average error vector magnitude for this case. The average number of tones in error per DMT symbol in this case is 8.27 tones. With the bandstop filter, the performance improved only slightly.

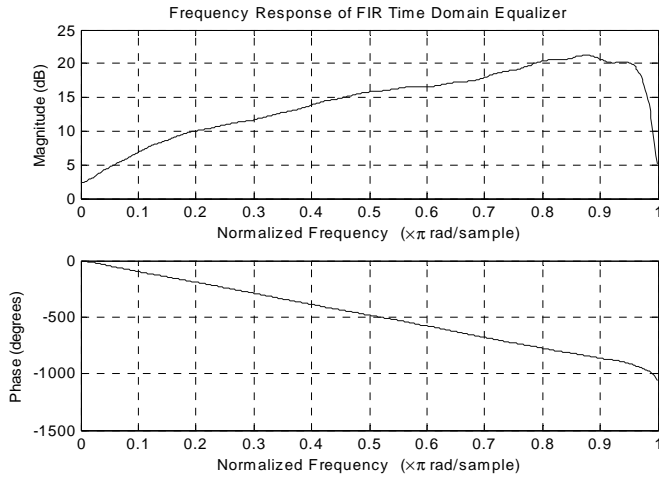


Figure 3: TEQ Response – Interference Free Channel

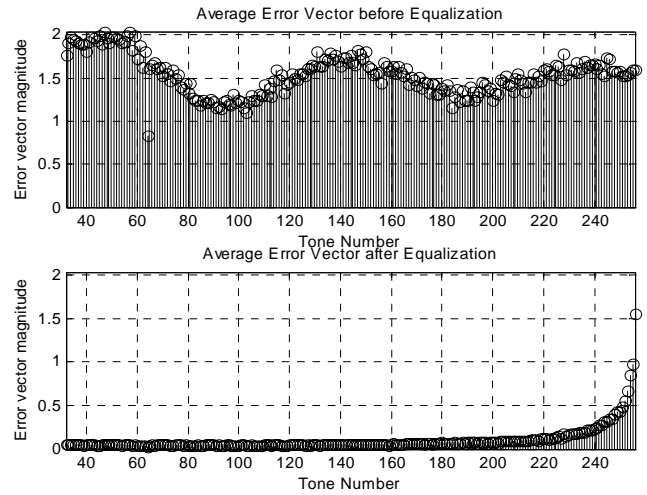


Figure 4: Average Error Vector Magnitude – Interference Free Channel

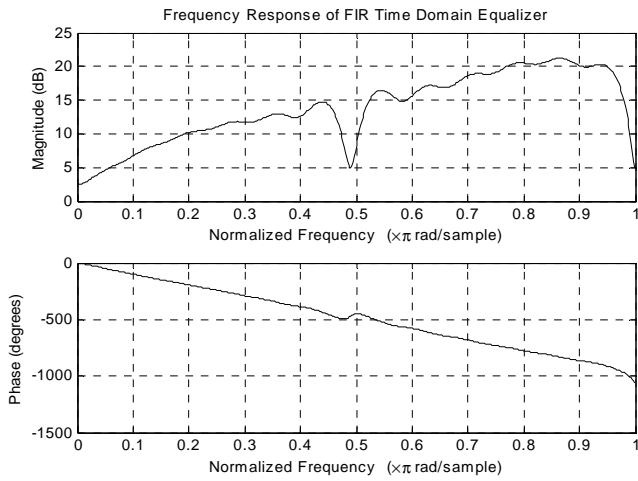


Figure 5: TEQ Response – RFI Plus Crosstalk

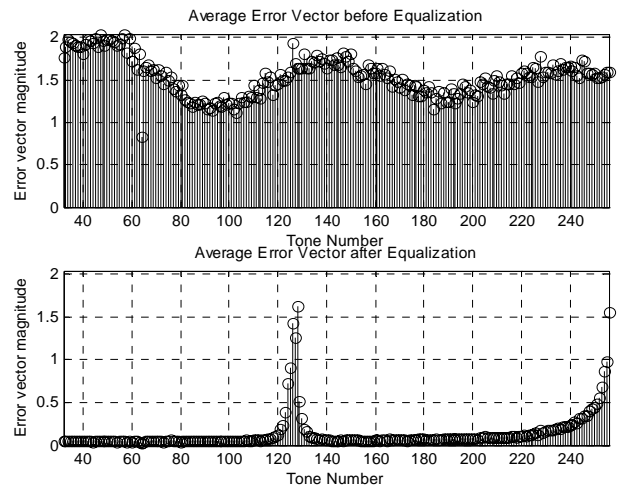


Figure 6: Average Error Vector Magnitude – RFI Plus Crosstalk

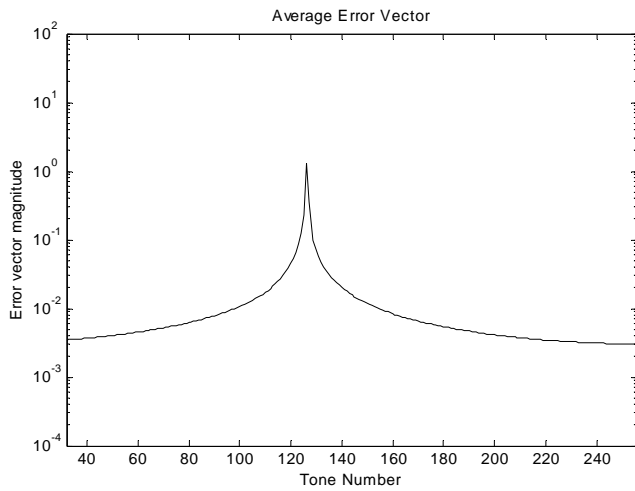


Figure 7: Ideal Channel With Single Sinusoidal Ingress Source

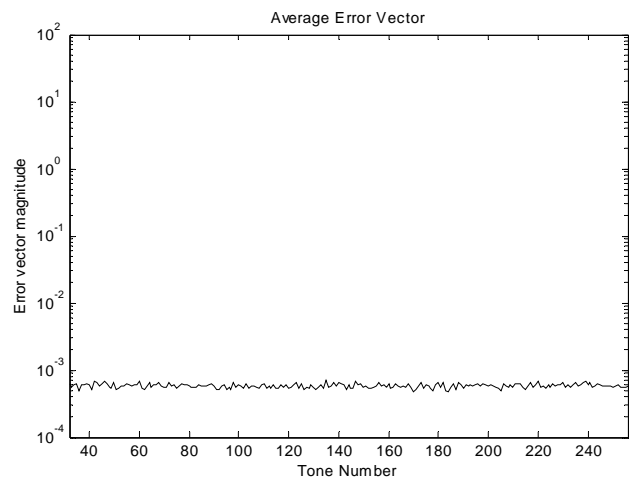


Figure 8: Ideal Channel With AWGN

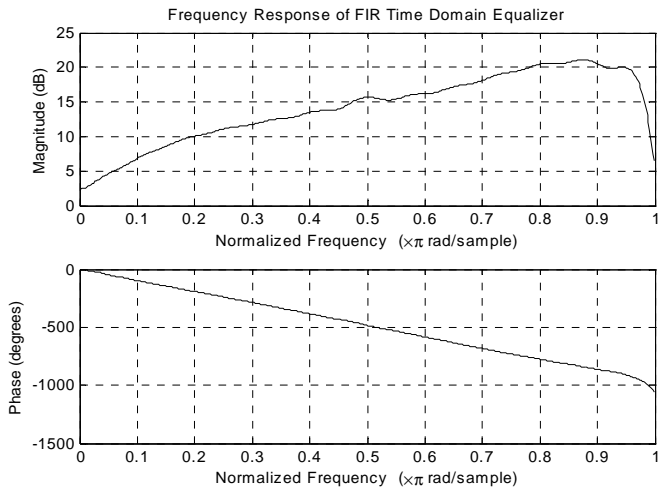


Figure 9: TEQ Response – Bandstop Filter Preprocessing

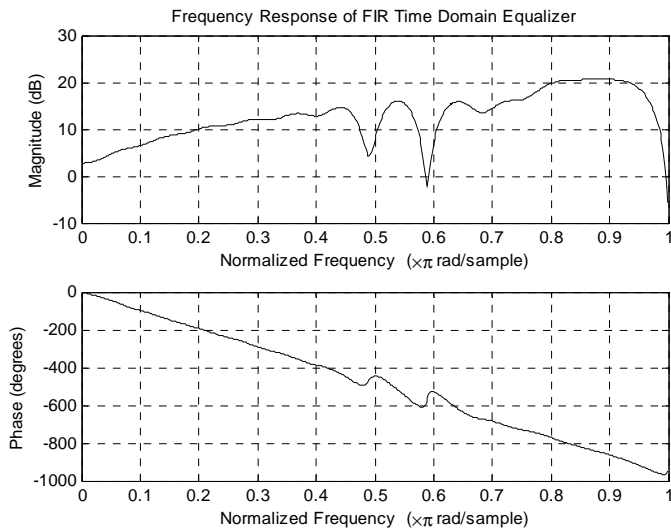


Figure 11: TEQ Response – Modulated G.test RFI Model I

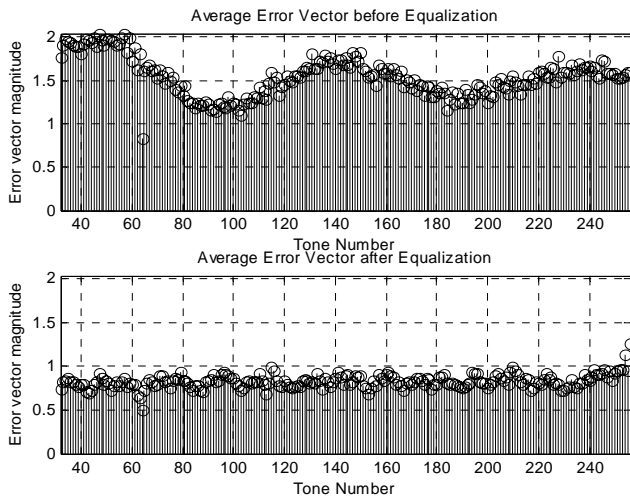


Figure 13: Average Error Vector Magnitude – Windowed FFT

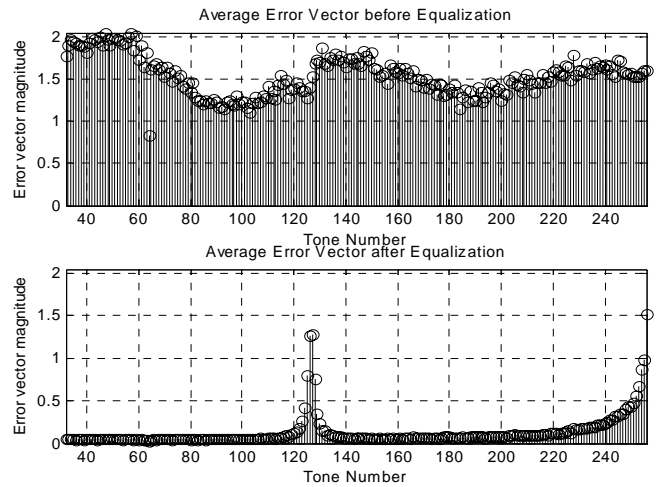


Figure 10: Average Error Vector Magnitude –Bandstop Filter Preprocessing

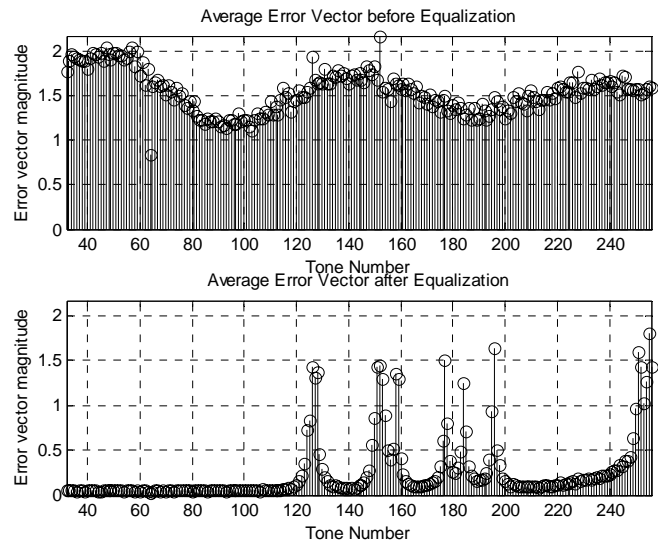


Figure 12: Average Error Vector Magnitude –Modulated G.test RFI Model I

Case 3: Modulated G.test RFI Model I (Multiple Ingress Sources)

Figures 11 and 12 show the equalizer frequency response and average error vector magnitude for this case. In the presence of multiple modulated interferers at the frequencies and power levels defined in G.test, the average number of tones in error per DMT symbol is 25.16. As expected, in the presence of multiple interferers the capacity of the DSL link decreases significantly.

Case 4: Windowed FFT

The Harris *et al* paper [1] concludes that a narrowband interferer causes a drastic capacity reduction as a result of the energy spreading, or “spectral leakage”, due to the linear DFT operation. They state that as uniform or rectangular windowing is done implicitly in the conventional DFT, the spreading of narrowband interferer energy to frequencies far off from its center occurs. The rectangular window has side lobes which are only 13 dB below the main lobe at their maximum. It is also

suggested by Harris *et al* [1] that using other window functions might improve the achievable data rate. Windows other than the rectangular window do not have nulls at $2f_s/N$ [5, cf. pg 84 Figure 3-16]. This causes major problems in taking the FFT because immediately adjacent tones are not nulled out by these windows.

The interference free channel case was run with windowing at the receiver and one can see how plainly applying windowing will not help in recovering the data. A Hanning window was used to perform the windowed FFT. The average number of tones in error per DMT symbol in this case is 164.35 tones. Figure 13 shows the average error vector magnitude for this case.

Case	Number of Tones in Error			
	Average		Max	Min
	Tones	%		
Interference Free Channel	4.96	2.13	9	2
RFI Plus Crosstalk	9.43	4.05	13	6
Bandstop Filter Preprocessing	8.27	3.55	13	4
Modulated RFI Model I	25.16	10.8	31	18
Windowed FFT	164.35	164.35	178	147

Table 1: Capacity Reduction

Table 1 summarizes the capacity reduction in terms of number of tones in error. All simulations were run with the transmitted DMT signal average power of about 17dBm and a loop length of 0.5 mile. When the RFI Plus Crosstalk case was rerun with a DMT symbol of power 20dBm, the average capacity reduction was 9.02 tones per DMT symbol. As the number of interference sources increases, the capacity reduction increases. When the G.test multiple interferer model is used, the modulated noise case causes greater capacity reduction than the unmodulated noise case.

To see how the loop length affects the capacity in the presence of RFI, the RFI plus crosstalk case with modulated G.test RFI noise was run for loop lengths of 0.25, 0.5 and 1 mile. From the results in Table 2 one can see that as distance increases, the DSL link capacity decreases.

Distance (mile)	Number of Tones in Error			
	Average		Maximum	Minimum
	Tones	%		
0.25	16.41	7.04	24	11
0.5	25.16	10.8	31	18
1	63.04	27.06	73	53

Table 2: Capacity Reduction vs. Loop Length – Modulated G.test RFI Model I

5. CONCLUSION

From the analysis of the results obtained, it is seen that spectral spreading of the narrowband interferer due to rectangular windowing is a cause of capacity reduction, but only at long loop lengths where the signal to Gaussian noise ratio is very low. It is also shown that directly applying other windows does not help in reducing the spectral spreading of the interferer. For a more detailed discussion of simulation cases and background work, refer to reference [6].

6. ACKNOWLEDGEMENT

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