8PSK SIGNALING OVER NON-LINEAR SATELLITE CHANNELS

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ABSTRACT

Space agencies are under pressure to utilize better bandwidth-efficient communication methods due to the actual allocated frequency bands becoming more congested. Budget reductions is another problem that the space agencies must deal with. This budget constraint results in simpler spacecraft carrying less communication capabilities and also the reduction in staff to capture data in the earth stations. It is then imperative that the most bandwidth efficient communication methods be utilized. This paper gives the results of a computer simulation study on 8 Level Phase Shift Keying (8PSK) modulation with respect to bandwidth, power efficiency, spurious emissions, interference susceptibility and the non-constant envelope effect through a non-linear channel. The simulations were performed on a Signal Processing Worksystem (SPW : software installed on a SUN SPARC 10 Unix Station and Hewlett Packard Model 715/100 Unix Station). This work was conducted at New Mexico State University (NMSU) in the Center for Space Telemetry and Telecommunications Systems in the Klipsch School of Electrical and Computer Engineering.

KEY WORDS

8PSK Modulation, Spectrum Shaping, Power Efficiency, Spurious Emissions, Non-Constant Envelope

INTRODUCTION

During its 12th annual meeting (November 1992 in Australia), the Space Frequency Coordination Group (SFCG-12) requested the Consultative Committee for Space Data Systems (CCSDS) Radio Frequency (RF) and Modulation Subpanel to study and compare various modulation schemes with respect to the bandwidth needed, power efficiency, spurious emissions and interference susceptibility.

An End-to-End system performance, including the InterSymbol Interference (ISI) and the Symbol Error Rate (SER) as a function of Es/No on 8PSK modulation was conducted on SPW software installed on a SUN Sparc Station 10 and a HP Model 715/100 Unix Station at NMSU. The simulations were based on the Non-Return-to-Zero Logic (NRZ-L) data format. The end-to-end system evaluation was performed using ideal and non-ideal data with ideal system components and three baseband filter types: 5th Order Butterworth, 3rd Order Bessel and Square Root Raised Cosine (SRRC), $\alpha = 0.25$, 0.5 and 1, to observe the effect of pulse shaping on bandwidth and SER. Ideal data are defined as having a perfect symmetry, i.e., the duration of a digit one (1) is equal to the time duration of a digit zero (0) and it also has a perfect data balance, i.e., the probability of getting a zero is equal to the probability of getting a 1 ($Pr(0) = Pr(1) = 0.5$ or 50%). For non-ideal data these two conditions, data symmetry and data balance, are not respected. The CCSDS limits are $\pm$ 2% for data asymmetry and a data imbalance of 0.45 (probability of getting a 1 vs probability of a 0) as mentioned in [1]. If non-ideal data are present (i.e., the mean value or expected value, m_a , of the signal is not equal to 0), the Power Spectrum Density (PSD) of the digital signal will then consist not only of a continuous spectrum that depends on the pulse-shape spectrum of the signal data (rectangular pulse for NRZ-L), but will also contain spectral lines (delta functions or spurious emissions) spaced at approximately the harmonics of the symbol rate, R_s . The PSD equation of a baseband digital signal for the case of uncorrelated data is derived in [2]. To complete this work, the relationship between the non-constant envelope introduced by pulse shaping the 8PSK signal and the bandwidth of the filter was to be investigated. Note that many analyses were performed on pulse shaping, non-constant envelope and non-linear channels, but none of them involved the measurement of the effect of a non-constant envelope signal (8PSK for this case) through a non-linear channel (SSPA).

First a general SPW block diagram used for the simulations will be described. Afterwards the results of the simulations with respect to the power containment, spurious emissions, SER and non-constant envelope effect on the bandwidth for different types of spectrum shaping filters are given. Finally conclusions of the work on 8PSK conducted at NMSU are given at the end of this paper.

COMPUTER SIMULATION TEST SYSTEM

Figure 1 shows the different blocks that were simulated on SPW.

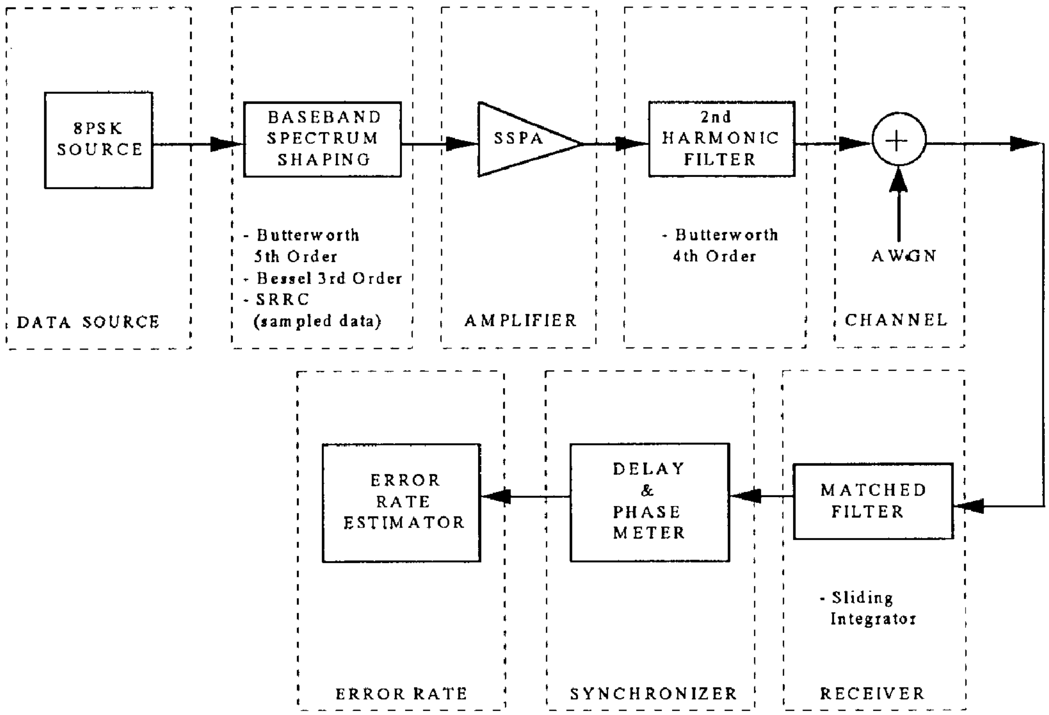

Figure 1 - Simulation Block Diagram

First a Data Source or Modulator was used to produce the 8PSK signal. The data source also contained a block that could produce data asymmetry on the data. All simulations were produced at baseband using the complex envelope signal representation. The results do not vary if the simulations are done in baseband or passband. The advantage of going to baseband is the computer execution time, i.e., it takes longer to simulate at passband since the sampling frequency must be at least twice the Nyquist rate. The next block after the modulator is the baseband spectrum shaping filter. The three types of filters that were used for these simulations were 5th Order Butterworth, 3rd Order Bessel, and finally Square Root Raised Cosine (SRRC) with Sampled Data and Roll-Off factors of 0.25, 0.5 and 1.

The next blocks include the Solid State Power Amplifier (SSPA), a bandlimiting filter and the noise (channel). Simulations were performed using the SSPA at the saturation level to maximize the power. NMSU used the SSPA model for their simulation which is based upon specifications provided by the European Space Agency (ESA) for their 10 Watts, solid state, S-band power amplifier. This amplifier was followed by a 2^{nd} Harmonic filter (4^{th} Order Butterworth with a bandwidth of ± 20Rs) which reduces the interference between different channels. This bandlimiting filter is followed by a variable Additive White Gaussian Noise (AWGN) block. These blocks were followed by the Receiver, Symbol Synchronizer and finally the Error Estimator. A matched filter was used as the receiver for the Butterworth and Bessel Filters. The matched filter was matched to the NRZ-L baseband data. For the SRRC, the receiver was also a SRRC to minimize the ISI. The SRRC will minimize the ISI and the matched filter is an optimum filter which optimizes the Signal-to-Noise ratio (SNR). The synchronizer that was used consisted in a Delay & Phase Meter that would correlate the initial data with the data that went through the channel. After these two signals went through the Delay & Phase Meter, the initial data were delayed to be synchronized with the distorted data (the delay between the initial and distorted data were caused by the filters). After the data were synchronized, an Error Rate Estimator was used to measure the differences in symbols and calculate the SER.

SIMULATION RESULTS

Power Containment and Spurious Emissions : As an example of the Power Containment simulations that were performed, Figure 2 shows the output of the SSPA without a spectrum shaping filter being used and Figure 3 shows the output of the SSPA when a 5th Order Butterworth (BT=1) is used as a spectrum shaping filter (non-ideal data is used).

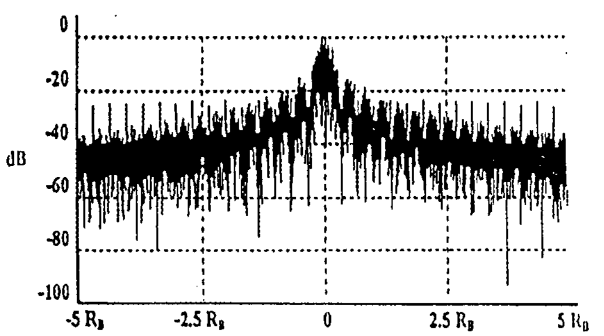

Figure 2 - Power Spectra: Output of SSPA at Saturation Level (No Baseband Filtering)

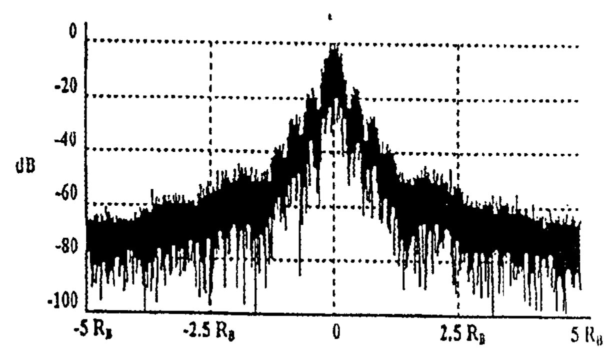

Figure 3 - Power Spectra: Output of SSPA at Saturation Level (Baseband Filtering: 5th Order Butterworth BT=1)

Note that at approximately $\pm$ 2R_B in Figure 3, the filter attenuates the data sidebands by approximately 40 dB. Also due to the non-constant envelope of the data (since some spectrum shaping was performed), the output of the SSPA is quite different from Figure 2. In fact, it seems like the SSPA is trying to recreate the sidelobes that were attenuated by the filter. Also, the spurious emissions encountered in simulations with the unfiltered case and non-ideal data case are not present or are fairly attenuated. It was found that in-band spurious emissions are more present and more evident for the Bessel Filter than the Butterworth Filter (Bandwidth-symbol Time product : BT=1) (refer to [4]). With respect to the sideband attenuation, it was found that the values of attenuation for the 3rd Order

Bessel are comparable to the 5th Order Butterworth. For SRRC filters with $\alpha = 0.25$ and $\alpha = 0.5$, the bandwidth is narrower than the Butterworth and Bessel Filters but the attenuation is less at high frequencies. Nonetheless, the absence of spurious emissions is a net advantage. For SRRC $\alpha = 1$, the bandwidth is wider than the two previous SRRC filters and the absence of in-band spurious emissions was again noticed. Less sideband attenuation was recorded for this roll-off factor compared with $\alpha = 0.25$ and $\alpha = 0.5$. To see the overall effect of spectrum shaping a frequency band Utilization Ratio (ρ) was defined as :

$$\rho = \frac{\text{Number of Spacecraft with Filtering Accommodated in Frequency Band}}{\text{Number of Spacecraft without Filtering Accommodated in Frequency Band}}$$

This ratio is an estimate of how many more spacecraft using a specific frequency band, can be included in the bandwidth using spectrum shaping filtering as opposed to no filtering. The following assumption in deriving this ratio was made: the spectra from spacecraft in adjacent channels will be permitted to overlap one another provided that, at the frequency where the overlap occurs, the signals are at least 50 dB below that of the main telemetry lobe (1st data sideband). Using SPW, measurements were made using unfiltered and non-ideal data to determine the frequency at which the data spectrum was 50 dB below the main lobe. Power Spectrum plots like the one shown earlier were used to determine this 50 dB level. For example, for ideal data without a spectrum shaping filter the -50dB point is situated at approximately 35 R_B (extrapolation of Figure 2) and using the Butterworth Filter (BT=1) with Ideal Data, the -50 dB point is approximately at 2.5 R_B (refer to Figure 3), then the Utilization ratio, ρ, is equal to $\rho = \frac{35R_B}{2.5R_B} = 14$.

Note that the way the ratio is calculated in this example is different from the formula given previously but the result is the same i.e. the number of spacecraft with filtering accommodated in the frequency band will be larger than if it was not filtered. Table 1 summarizes the calculations of the Utilization ratio, ρ, for the spectrum shaping filters that were used.

From Table 1 it is obvious that baseband filtering offers a significant improvement in the number of spacecraft operating in a frequency band. In fact by baseband filtering, the bandwidth utilization can increase by a factor of 12 to 24.

<u>End-to-End System Performance: Symbol Error Rate S(ER)</u> : To measure the End-to-End system performance, the SER was measured for different values of average symbol energy to noise ratios (Es/No). Such a measurement was performed using SPW and the system described previously. The three types of baseband filters described earlier were used. To choose the best filter from such a study one selects the filter that has a BT product such that the filter ISI loss is < 0.4 dB (refer to [3]). To obtain a measure of the filter ISI loss, a

FILTER TYPE	Ideal Data -50 dB pt.	Ideal Data Util. Ratio (ρ)	Non-Ideal Data -50 dB pt.	Non-Ideal Data Util. Ratio (ρ)
None, Unfiltered Data (Reference	35 R_B	1	40 R_B	1
Butterworth, 5th Order (BT=1)	2.5 R_B	14	2.3 R_B	17.39
Bessel, 3rd Order (BT=1)	2.95 R_B	11.86	2.5 R_B	16
Square Root Raised Cosine (α = 0.25) Sampled Data	1.7 R_B	20.59	1.7 R_B	23.5
Square Root Raised Cosine (α = 0.5) Sampled Data	1.8 R_B	19.4	1.7 R_B	23.5
Square Root Raised Cosine α = 1) Sampled Data	2.5 R_B	14	2.2 R_B	18.18

Table 1 - Utilization Ratio Improvement for Various Spectrum Shaping

reference needed to be established. An ideal linear system is used where ideal data and hardware are utilized to provide a reference for comparisons with the system being studied (a plot of Probability of error versus Es/No is derived and called Theoretical plot in this case for 8PSK [2]). Figures 4, 5 and 6, respectively, show the SER for 8PSK: 5th Order Butterworth BT=1, 2 and 3 (SSPA at Saturation & Ideal-Data), SER for 8PSK: 3rd Order Bessel BT=1, 2 and 3 (SSPA at Saturation & Ideal-Data) and SER for 8PSK: SRRC α=l (no SSPA), α=0.25, 0.5 and I (SSPA at Saturation & Ideal-Data). From these simulations it is then possible to determine the ISI loss due to the system. This is found by taking the difference between the Es/No values measured with and without the filter. As indicated in [3], the losses are measured over values of $10^{-3} \leq$ SER $\leq 10^{-2}$ which is the normal operating region for CCSDS encoded data. Losses are then tabulated for BT =1,2,3 (see Table 2). Also as indicated in that same report the optimal filter is found by selecting the lowest BT providing acceptable ISI loss (in this case a threshold of ISI loss < 0.4 dB). The following table gives the results of the baseband filter ISI losses at 10^{-3} SER using Figures 4, 5 and 6:

Note that only the loss of the SRRC with α=1.0 is shown in the table since the other SRRC filters have higher values of losses (as shown in Figure 6) and their bandwidths are much smaller than BT=1 therefore they can not be compared with the Butterworth or Bessel filters. It must be emphasized that these simulations were performed with ideal data therefore since these values of BT barely meet the ISI < 0.4 requirement, with a non-ideal system this threshold would not be met (add approximately 0.5 to 1.0 dB to the values

FILTER TYPE	LOSS (BT=1) (dB)	LOSS (BT=2) (dB)	LOSS (BT=3) (dB)
Butterworth 5th Order	17.86 - 15.68 = 2.18	16.29 -15.68 = 0.61	16.05 -15.68 = 0.37
Bessel 3rd Order	17.52 - 15.68 = 1.84	16.97 - 15.68 = 1.29	16.09 - 15.68 = 0.41
SRRC (α=1.0)	16.50 -15.68 = 0.82	----------	------------

Table 2 - Baseband Filters ISI Loss Measurements at 10^{-3} SER

measured). Thus a simulation with a higher order of BT should be performed (example BT = 4) which would certainly meet the above requirement since the bandwidth would be increased.

Non-Constant Envelope : Pulse shaping gives a smaller bandwidth but can produce a non-constant envelope which reduces the performance of the communication system. On the other hand, no pulse shaping gives a larger BW but the signal has a constant envelope which is a plus on the performance of the receiver filter. The trade-off between constant envelope and bandwidth (BW) then is worth investigating. The bandwidth and envelope variation were measured for different types of pulse shaping to observe the relationship betweem these two parameters. To analyze the effect of non-constant envelope going through the SSPA, different simulations where conducted on SPW with the 3 types of filters mentioned earlier. It was noted that the non-constant envelope going through the SSPA (at saturation level) creates a rotation (AM-PM conversion) and a spreading of the symbols (AM-AM conversion) as expected. Figures 7, 8 and 9 show the effect of varying the non-constant envelope of a signal (by using different BT or α) through an SSPA. The Average Symbol Variance is used as a parameter indicating the spreading of the symbol with respect to the mean for each of the 8 decision regions. For the 5th Order Butterworth Filter in Figure 7, it is noted that the variance substantially decreases in an exponential-sinusoidal manner. From BT= 1 to BT= 1.1, the values decrease rapidly which can be explained by the fact that for BT=1, the filter is narrower and contains only the main lobe of the power spectral density. Figure 8, shows the results of variance vs BT for the 3rd Order Bessel Filter. Again as in the Butterworth case presented earlier, the average variance gradually decreases in a sinusoidal form. The damping is more pronounced for the 3rd Order Bessel than the 5th Order Butterworth since the Bessel's variance starts to become a flat line around BT=1.8 but for the Butterworth Filter case the steady line becomes present around BT=3. Also note that the average variance is appreciably less in magnitude for the Bessel filter (order of magnitude ≈ 10^{-4}) than the Butterworth filter (order of magnitude ≈ 10^{-2}) . Finally Figure 9 shows the average variance versus the roll-of factor (α) for the SRRC filter. In this case note that the aspect of the plot is really different

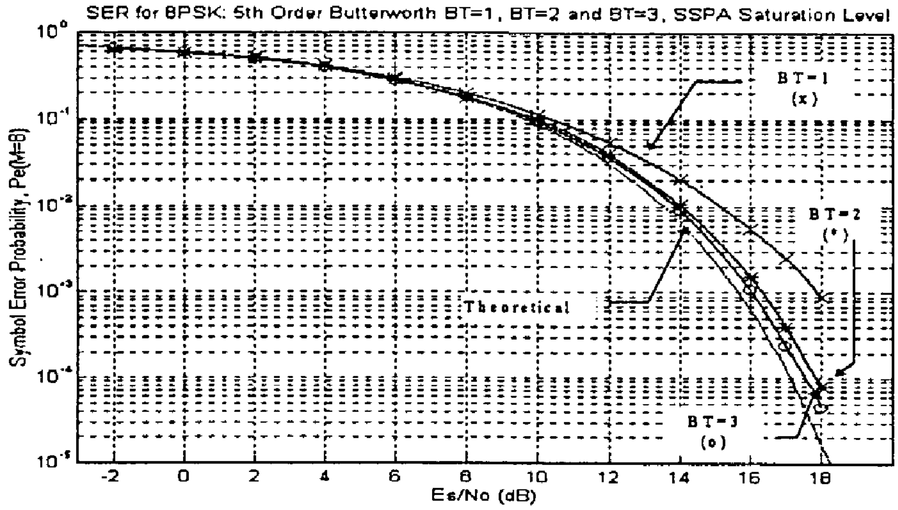

Figure 4 - SER for 8PSK:5th Order Butterworth BT=1,2 and 3

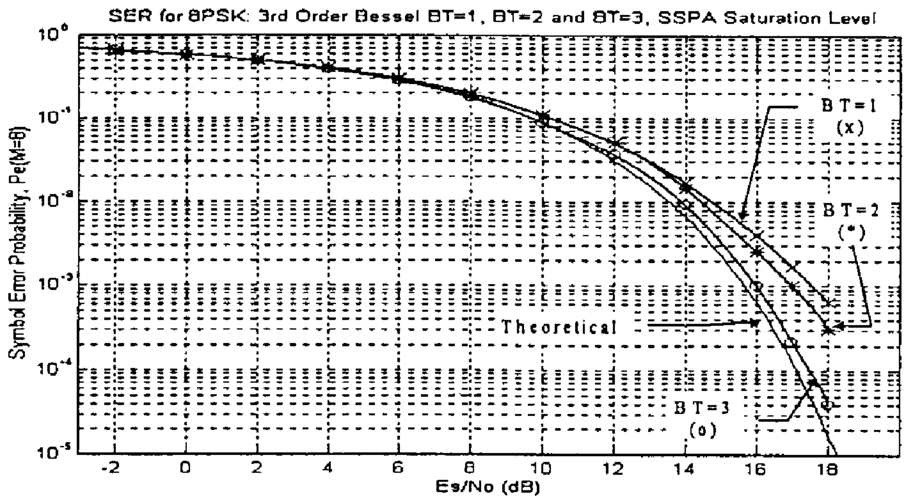

Figure 5 - SER for 8PSK: 3rd Order Bessel BT = 1, 2 and 3

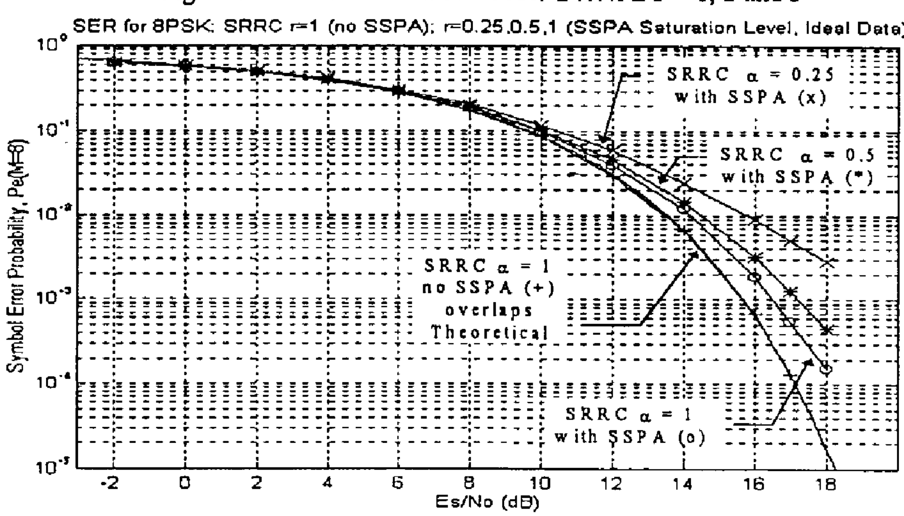

Figure 6 - SER for 8PSK: SRRC $\alpha = 1$ (no SSPA), $\alpha = 0.25$, 0.5 and 1

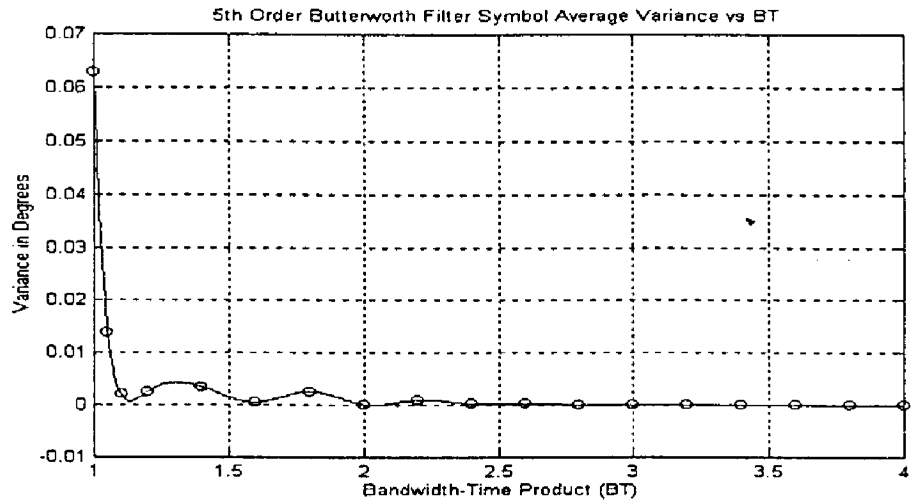

Figure 7 - 5th Order Butterworth Filter: Average Symbol Variance vs BT

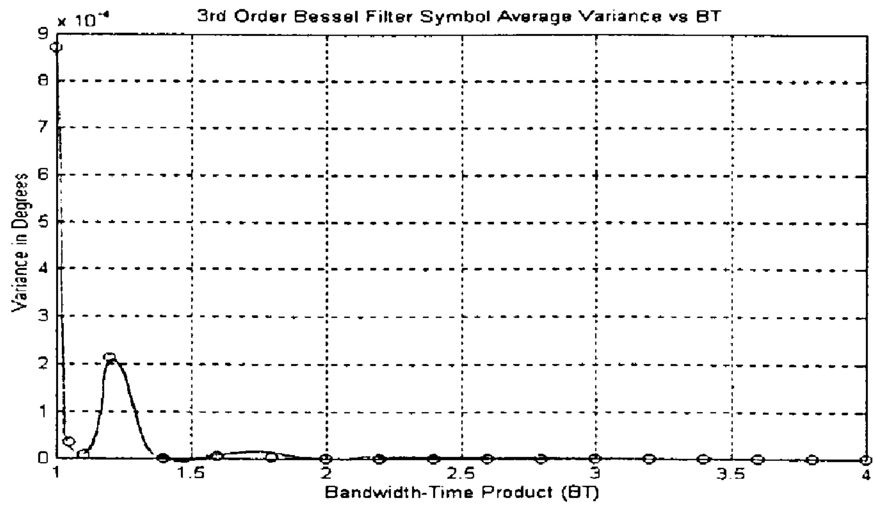

Figure 8 - 3rd Order Bessel Filter: Average Symbol Variance vs BT

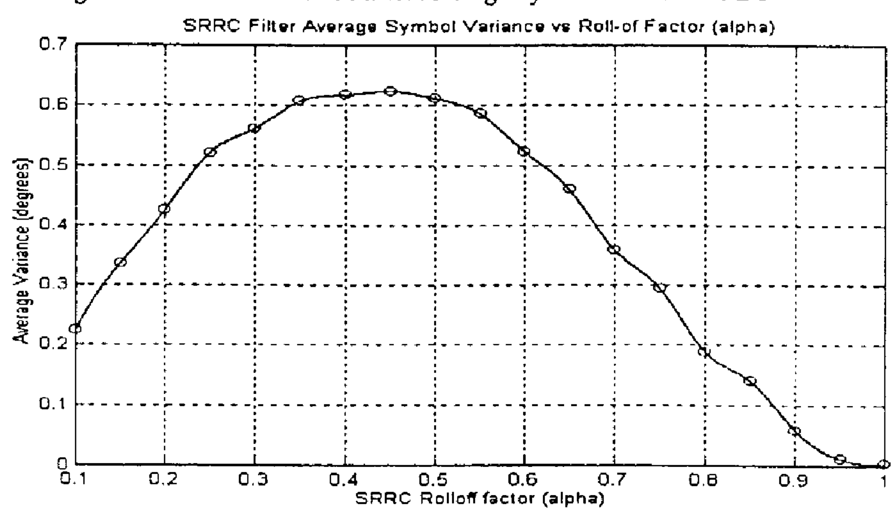

Figure 9 - SRRC: Average Symbol Variance vs Roll-off factor (α)

from the two previous filters. In fact, for the SRRC, the plot appears to have the aspect of a parabola with a maximum at approximately α=0.45. Note that simulations could not be performed for $0 \leq \alpha < 0.1$ due to SPW software limitations. Nonetheless, it can be seen that the curve gradually decreases to 0 as α reaches 0. This can be explained by the fact that for α=0, the frequency response of a SRRC is a pure square wave (or "brick wall"). Thus in the time domain, it would then correspond to a pure sinc (sin(x)/x) function which would have the zero crossings at the sampling frequency therefore eliminating any ISI. For the case where α reaches 1, the average variance also decreases toward 0 (but it does not reach it). This can be explained since the SRRC filter has a bigger BW for higher α therefore allowing more of the power spectrum to be included in the transmission; this is the same result as increasing the BT for the Butterworth or Bessel Filter. Finally note how the magnitude of the average variance is larger for the SRRC filter than the Butterworth and Bessel.

CONCLUSIONS

From the simulations on 8PSK Baseband Filtering performed in the Center for Space Telemetering and Telecommunications Systems at NMSU, the following conclusions can be made on the PSD, SER and Non-Constant Envelope. With respect to PSD and SER for the 8PSK signal, in-band spurious emissions are more present and more evident for the Bessel Filter than the Butterworth Filter (BT=1). With respect to the sideband attenuation, it was found that the values of attenuation for the 3rd Order Bessel are comparable to the 5th Order Butterworth. For SRRC filters with α = 0.25 and α = 0.5, the bandwidth is narrower than the Butterworth and Bessel Filters but the attenuation is less at high frequencies. Nonetheless, the absence of spurious emissions is a net advantage. For SRRC α = 1, the bandwidth is wider than the two previous SRRC filters and the absence of in-band spurious emissions was again noticed. Less sideband attenuation was recorded for this roll-off factor compared with α = 0.25 and α = 0. 5. For SER, it was found that the Butterworth and Bessel Filters just barely meet the threshold of ISI loss < 0.4 dB at SER = 10^{-3}. Also the SRRC filters do not meet this specification. Overall, it was shown by using baseband filtering that the bandwidth utilization can be improved by a factor of approximately 12 to 24 with BT=1 and 8PSK (see Table 1 in this report) which can significantly increase the spectrum utilization.

To increase our knowledge with respect to a non-linear satellite channel, specific measurements were performed on the Non-Constant Envelope of the signals going through the non-linear SSPA. These simulations have not been previously reported. It was found that the amplitude of the Average Symbol Variance of the signal using the 3rd Order Bessel is much less than for the 5th Order Butterworth Filter. Also the amplitude for the 3rd Order Bessel Filter damps toward zero around BT=1.8 whereas for the 5th Order Butterworth Filter this damping will occur around BT=3. These curves have the aspect of a sinusoidal function decreasing exponentially toward zero. Finally the Average Symbol Variance vs α for the SRRC was found to be quite different than the two previous spectrum shaping filters. This plot looks more like a parabola with a maximum at approximately $\alpha = 0.45$. For the non-constant envelope simulations more simulations should be performed using different orders of filters for Butterworth and Bessel. From these simulations it might be possible to find a general expression on how the variance of the symbols is altered by changing BT. This expression should have the following form: a*exp(-x)*sin(x) for the Butterworth and Bessel Filters. It would then be possible to predict, with a general equation, when the BT has no real effect on the shaping of a pulse.

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