Spectral Re-growth Reduction for CCSDS 8-D 8-PSK TCM

by

Deva K. Borah

NMSU-ECE-02-006

UNCLASSIFIED

NMSU Technical Report No. NMSU-ECE-02-006

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Prepared for NASA
under Grant # NAG 5-9323

October 2002

UNCLASSIFIED

Abstract

This report presents a study on the CCSDS recommended 8-dimensional 8 PSK Trellis Coded Modulation (TCM) scheme. The important steps of the CCSDS scheme include: conversion of serial data into parallel form, differential encoding, convolutional encoding, constellation mapping, and filtering the 8-PSK symbols using the square root raised cosine (SRRC) pulses. The last step, namely the filtering of the 8 PSK symbols using SRRC pulses, significantly affects the bandwidth of the signal. If a nonlinear power amplifier is used, the SRRC filtered signal creates spectral regrowth. The purpose of this report is to investigate a technique, called the smooth phase interpolated keying (SPIK), that can provide an alternative to SRRC filtering so that good spectral as well as power efficiencies can be obtained with the CCSDS encoder.

The results of this study show that the CCSDS encoder does not affect the spectral shape of the SRRC filtered signal or the SPIK signal. When a nonlinear traveling wave tube amplifier (TWTA) is used, the spectral performance of the SRRC signal degrades significantly while the spectral performance of SPIK remains unaffected. The degrading effect of a nonlinear solid state power amplifier (SSPA) on SRRC is found to be less than that due to a nonlinear TWTA. However, in both cases, the spectral performance of the SRRC modulated signal is worse than that of the SPIK signal.

The bit error rate (BER) performance of the SRRC signal in a linear amplifier environment is about 2.5 dB better than that of the SPIK signal when both the receivers use algorithms of similar complexity. In a nonlinear TWTA environment, the SRRC signal requires accurate phase tracking since the TWTA introduces additional phase distortion. This problem does not arise with SPIK signal due to its constant envelope property. When a nonlinear amplifier is used, the SRRC method loses nearly 1 dB in the bit error rate performance. The SPIK signal does not lose any performance. Thus the performance gap between SRRC and SPIK reduces. The BER performance of SPIK can be improved even further by using a more optimal receiver. A similar optimal receiver for SRRC is quite complex since the amplifier distorts the pulse shape. However, this requires further investigation and is not covered in this report.

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Acknowledgements

The author would like to thank Pen-Shu Yeh of Goddard Space Flight Center for her valuable comments.

1 Summary

This report presents a study on the CCSDS recommended 8-dimensional 8 PSK Trellis Coded Modulation (TCM) scheme. The important steps of the CCSDS scheme include conversion of serial data into parallel form, differential encoding, convolutional encoding, constellation mapping, and filtering the 8-PSK symbols using the square root raised cosine (SRRC) pulses. The last step, namely the filtering of the 8 PSK symbols using SRRC pulses, significantly affects the bandwidth of the signal. If a nonlinear power amplifier is used, the SRRC filtered signal creates spectral regrowth. This report investigates a technique, called the smooth phase interpolated keying (SPIK), that can provide an alternative to SRRC filtering so that good spectral as well as power efficiencies can be obtained with the CCSDS encoder.

The most important step in the SPIK modulation is phase interpolation. This is performed by using splines over the phase values. Symbols over several periods comprise a window, and the phase values of the symbols over each window are fitted with a spline. The interpolated values during the middle of the window are only retained. These are converted into transmitted samples. The window then slides in time by one symbol interval and new transmitted samples are generated. Since only the phase values are changed, the signal remains constant envelope. Hence the modulation is suitable for nonlinear power amplification. It is observed that SPIK is highly bandwidth efficient achieving about 30% efficiency compared to Gaussian Minimum Shift Keying (GMSK) at -50 dB while maintaining similar bit error rate (BER) performance.

We observe in this study that the CCSDS encoder does not affect the spectral shape of the SRRC filtered signal or the SPIK signal. When a nonlinear traveling wave tube amplifier (TWTA) is used, the spectral performance of the SRRC signal degrades significantly while the spectral performance of SPIK remains unaffected. The degrading effect of a nonlinear solid state power amplifier (SSPA) on SRRC is found to be less than that due to a nonlinear TWTA. However, in both cases, the spectral performance of the SRRC modulated signal is worse than that of the SPIK signal when a nonlinear amplifier is used.

The bit error rate (BER) performance of a linearly amplified SRRC signal is about 2.5 dB better than that of the SPIK signal when both the receivers use algorithms of similar complexity. In a nonlinear TWTA environment, the SRRC signal requires accurate phase tracking since the TWTA introduces additional phase distortion. This problem does not arise with SPIK signal due to its constant envelope property. In a nonlinear amplifier environment, the SRRC method loses nearly 1 dB in the bit error rate performance. The SPIK signal does not lose any performance. Thus the performance gap between SRRC and SPIK reduces. The BER performance of SPIK can be improved even further by using a more optimal receiver. A similar optimal receiver for SRRC is quite complex since the amplifier distorts the pulse shape. However, this requires further study and is not covered in this report.

2 Introduction

CCSDS has recommended multi-dimensional 8-PSK Trellis Coded Modulation (TCM) for high data rate channels generally used in Earth Exploration Satellite missions. This modulation comprises of a serial to parallel converter, a trellis encoder, a constellation mapper, and an 8-PSK modulator. The 8-PSK symbols are filtered with a square root raised cosine (SRRC) filter with a roll-off factor of 0.35 or 0.5. This filtering restricts the bandwidth occupied by the transmitted signal. At the receiver side, an SRRC matched filter, with the same roll-off factor as used at the transmitter side, is used for filtering and sampling the received noisy signal. The received samples are then processed in order to extract the information.

The use of the SRRC filter at the transmitter side results in a highly spectrally efficient signal when a linear amplifier is used. Unfortunately, linear amplifiers are not as power efficient as nonlinear amplifiers. However, when a nonlinear amplifier is used, the SRRC filtered signal gives rise to significant spectral re-growth affecting the bandwidth efficiency of the system. Hence there is a need to look at the performance degradation of such systems and to explore new techniques to improve the spectral efficiency.

In this report, we consider a modulation technique, referred to as the Smooth Phase Interpolated Keying (SPIK). This method uses a smooth interpolation of the phases of the transmitted symbols. The interpolation is performed by using splines over the phase values. Symbols over several periods comprise a window, and the phase values of the symbols over each window are fitted with a spline. The interpolated values in the middle of the window are only retained. These are converted into transmitted samples. The window then slides in time by one symbol interval and new transmitted samples are generated. Since only the phase values are changed, the signal remains constant envelope. Hence the modulation is suitable for nonlinear power amplification.

This report presents the spectral performance results for conventional SRRC modulated symbols and SPIK modulated symbols when the CCSDS 8-D 8-PSK modulation is used. Both linearly and nonlinearly amplified cases are considered. The bit error performance for both SRRC and SPIK are presented, and critical comparisons are made.

This report is organized as follows. In the next section, a discussion on the CCSDS 8-D TCM and the SPIK modulation technique is presented, simulation set-up procedures are described and receiver structures are discussed. This section also presents models for the nonlinear amplifier. Section 4 describes the numerical results and their implications. Section 5 summarizes the study and, finally, Section 6 makes recommendations based on the findings of this report.

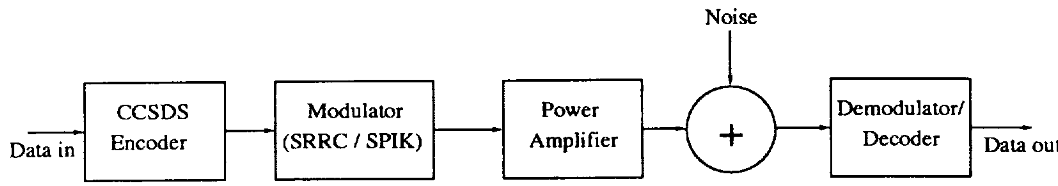

Figure 1: Block Diagram of the Communications System

3 Methods, Assumptions, and Procedures

This section briefly presents the CCSDS recommended TCM structure and then describes the Smooth Phase Interpolated Keying (SPIK). The basic block diagram of the system under consideration is shown in Fig. 1. Binary data, encoded by the CCSDS channel encoder, are modulated using one of the two techniques: (1) conventional square root-raised cosine (SRRC) filtered 8-PSK, and (2) 8-PSK SPIK. The modulated signal then passes through a nonlinear amplifier (NLA). Both a Traveling Wave Tube (TWT) amplifier and a solid state power amplifier (SSPA) are considered. The NLA produces considerable spectral spreading of the conventional SRRC modulated signal, thus seriously degrading the bandwidth efficiency of the system. In order to reduce the effects of nonlinear distortion, the operating point of the NLA is 'backed off' from saturation. However, a large amount of backoff reduces the available output power, and thus degrades the bit error rate performance of the system. Hence a meaningful comparison of modulation schemes must include studies on both spectral qualities and bit error rate (BER) performance.

3.1 CCSDS 8-D TCM

Near-earth missions are both power and bandwidth limited. Therefore, CCSDS recommends an 8-dimensional TCM scheme that provides a coding gain without compromising the bandwidth efficiency. The structure of the modulator is shown in Fig. 2. Serial data are converted into parallel form. Two possible architectures are considered: (i) 2 bits/symbol, and (ii) 2.5 bits/symbol. In the 2 bits/symbol case, $b = 8$ parallel bits are considered. Three of these bits are differentially encoded. One of the differentially encoded bits and two other bits are are used to produce four convolutionally encoded bits. The convolutional encoder thus has a rate 3/4, and its constraint length is 7 with 64 states.The output bits are mapped to 8 PSK constellation points in a natural way by a constellation mapper. The symbols are finally filtered by a square root raised cosine filter (SRRC).

3.2 Smooth Phase Interpolated Keying (SPIK)

Although the SRRC approach is recommended by the CCSDS, there is still a need to look at filtering techniques that may provide better spectral and power efficiencies, particularly in conjunction with a nonlinear amplifier. One such technique is the smooth phase interpolated keying (SPIK) [1]. The principle of SPIK for the CCSDS recommended scheme is shown in Fig. 3.

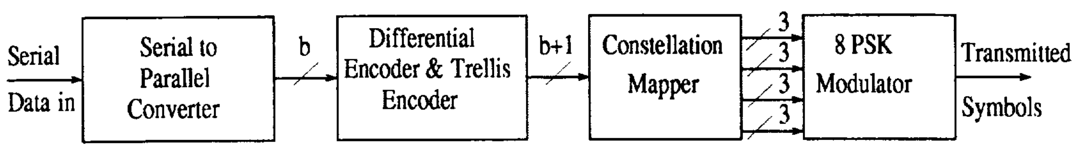

Figure 2: CCSDS 8-D 8-PSK TCM Encoder Block Diagram

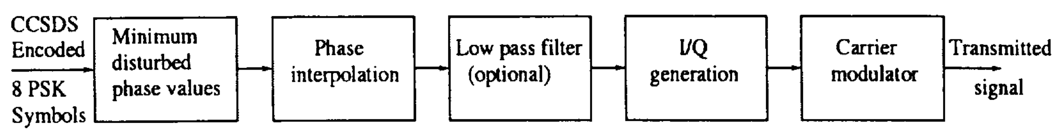

Figure 3: SPIK generation with CCSDS Encoded Data

The input to the SPIK generator is the sequence of CCSDS encoded symbols. Each 8-PSK symbol can have one of 8 possible phase values, $\pm 45^o$, $\pm 90^o$, $\pm 135^o$, and $\pm 180^o$. Therefore, the phase shift from one symbol to the next symbol is one of the phase values, 0^o,$\pm 45^o$, $\pm 90^o$, $\pm 135^o$, and $\pm 180^o$. The phase θ_i of the i-th symbol is obtained as

$$\theta_i = \theta_{i-1} + \Delta\theta_i$$

where $\Delta\theta_i$ is the phase shift of the i-th symbol with respect to the previous symbol. The phase shifts $+180^o$ and -180^o denote the same symbol. However, in order to reduce the spectral growth, the positive or the negaive sign of 180^o is chosen depending on the sign of the previous phase shift $\Delta\theta_{i-1}$. If $\Delta\theta_{i-1}$ is positive, then $+180^o$ is chosen, and if $\Delta\theta_{i-1}$ is negative, then -180^o is used. If $\Delta\theta_{i-1}$ is 0^o, then $\Delta\theta_{i-2}$ is considered instead of $\Delta\theta_{i-1}$, and the procedure is repeated. In this way, the minimum disturbed phase values shown in Fig. 3 are obtained.

The minimum disturbed phase values are next interpolated using cubic splines. In this report, a spline over 8 symbols is considered. Let these symbols during the i-th symbol period be $a_i, a_{i-1}, \cdots, a_{i-7}$. Each symbol duration is interpolated for $r = 16$ uniformly spaced points, and the middle portion of the spline (between symbols a_{i-3} and a_{i-4}) is retained. Next the spline is fitted over the symbols $a_{i+1}, a_i, a_{i-1}, \cdots, a_{i-6}$, and the interpolated phase samples between symbols a_{i-2} and a_{i-3} are retained. In this way, for every symbol period, a spline is fitted over the most recent 8 symbol phases, and the middle portion of the spline is used for transmission. The interpolated phase values can be filtered further to improve the spectral performance. Finally, the phase values are used to generate the In-phase (I) and Quadrature (Q) components, before being modulated with the carrier.

It is shown in [1] that SPIK using Offset QPSK (OQPSK) has better spectral properties than GMSK with $BT_b = 0.3$, while still providing better BER performance at the low SNR region. The BER performance at the high SNR region is very similar. Thus SPIK has both spectal and power advantages over GMSK with $BT_b = 0.3$, used in the Global Systems for Mobiles (GSM) standards.

3.3 Nonlinear Amplifier Modeling

Both TWTA and SSPA are considered. Let us consider the following signal as input to the nonlinear amplifier.

$$x(t) = m(t)\cos(\omega_c t + \psi(t)) \tag{3.1}$$

where ω_c is the carrier frequency, and $m(t)$ and $\psi(t)$ are the modulated envelope and phase, respectively. The output signal from the NLA is then described as

$$y(t) = A[m(t)]\cos(\omega_c t + \psi(t) + \Phi[m(t)]) \tag{3.2}$$

where $A[m(t)]$ is a function of $m(t)$ representing AM/AM conversion, and $\Phi[m(t)]$ is a function of $m(t)$, representing AM/PM conversion.

3.3.1 TWT Amplifier

The TWTA produces both AM/AM and AM/PM effects as [2],

$$A(m) = \frac{\alpha_a m}{1 + \beta_a m^2} \tag{3.3}$$

$$\Phi(m) = \frac{\alpha_\phi m^2}{1 + \beta_\phi m^2} \tag{3.4}$$

In our simulation study, we use $\alpha_a = 1.9638$, $\alpha_\phi = 2.5293$, $\beta_a = 0.9945$, and $\beta_\phi = 2.8168$. These values are directly taken from [2]. Accordingly, the AM/AM conversion and the AM/PM conversion curves are obtained as shown in Figs. 4 and 5 respectively.

3.3.2 SSP Amplifier

The output signal from a solid state power amplifier is described by the following AM/AM equation [3],

$$A(m) = \frac{m}{(1 + m^{10})^{\frac{1}{10}}} \tag{3.5}$$

The SSPA produces no AM/PM effects, and hence $\Phi(m) = 0$. The AM/AM conversion curve for the SSPA is shown in Fig. 6.

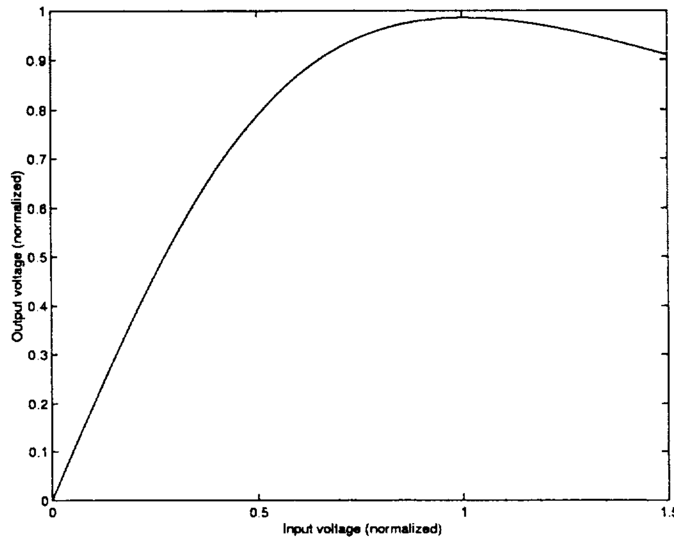

Figure 4: AM/AM characteristics of a commercial TWT

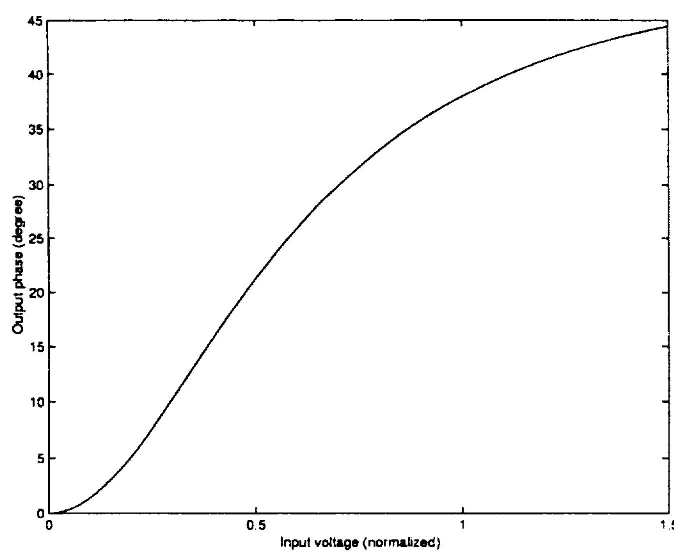

Figure 5: AM/PM characteristics of a commercial TWT

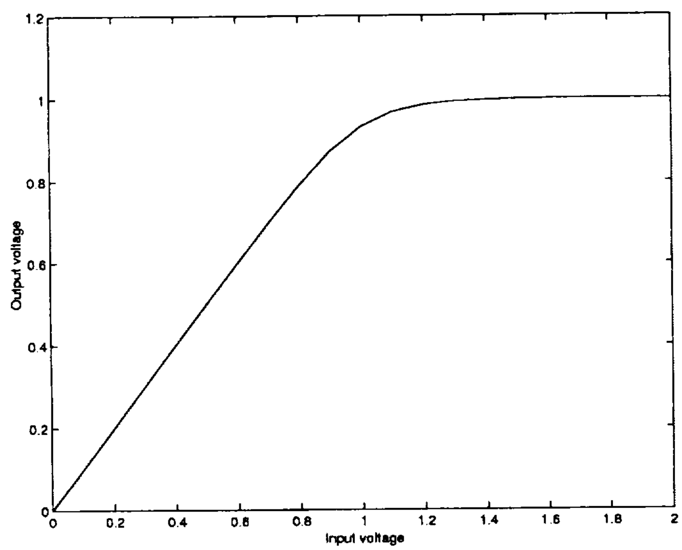

Figure 6: AM/AM characteristics of an SSPA

3.3.3 Input Back-off

The input backoff (IBO) in dB is defined as

$$\mathrm{IBO} = 10\log\left(\frac{P_{\mathrm{in}}^{\mathrm{sat}}}{\overline{P}_{\mathrm{in}}}\right) \tag{3.6}$$

where $P_{\mathrm{in}}^{\mathrm{sat}}$ is the input saturation power when the output power begins to saturate, and $\overline{P}_{\mathrm{in}}$ represents average input power. The complex signal (that is, including both I and Q channels), after energy scaling, is subjected to backoff scaling by multiplying with a constant γ given by

$$\gamma = \frac{1}{\sqrt{10^{\frac{\mathrm{IBO}}{10}}}} \tag{3.7}$$

As an example, for 0 dB backoff, the scaling factor γ becomes 1.

3.4 Receivers for SRRC

The complex envelope of the transmitted signal is

$$s(t) = \sum_i a_i p(t - iT) \tag{3.8}$$

where $\{a_i\}$ is the sequence of 8-PSK symbols from the CCSDS encoder, and $p(t)$ is the SRRC filter. This signal passes through the amplifier (typically an NLA), and is corrupted by additive

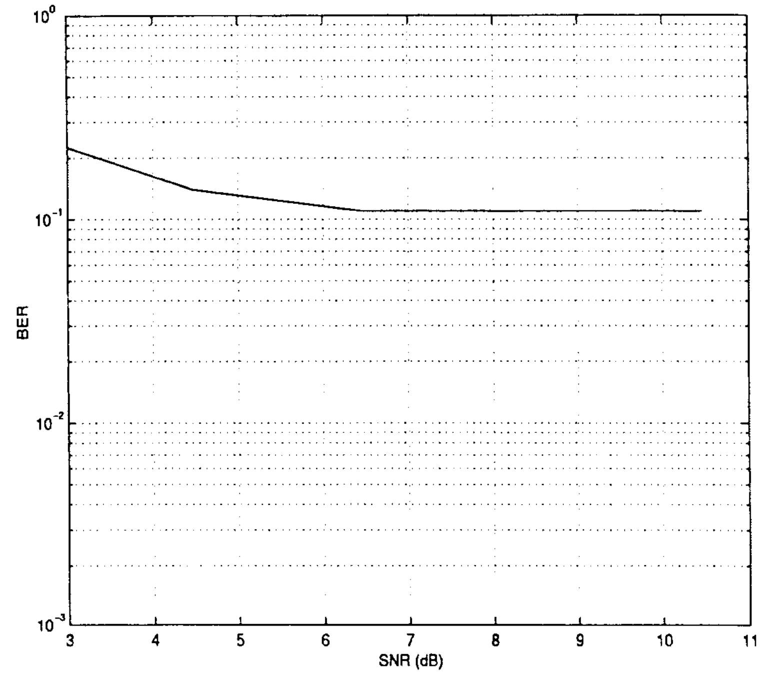

Figure 7: BER performance of SRRC (roll-off factor=0.35) when a TWTA is used without any phase compensation.

white Gaussian noise. Note that the signal amplitude $|s(t)|$ fluctuates over a large range. Therefore, if a TWT amplifier is employed, there will be significant phase distortion, as seen from the characteristics in Fig. 5. This phase distortion must be tracked at the receiver for good performance. The performance of the receiver without phase tracking is shown in Fig. 7.

On the receiver side, the received signal is first matched with an SRRC pulse, and samples at the symbol rate are taken. These samples are then fed into a Viterbi algorithm (VA) [4] with 64 states.

3.5 Receivers for SPIK

Different types of receivers can be considered for SPIK. A simple receiver consists of a low pass filter (LPF) and Viterbi algorithm. The LPF considered in this report is a Butterworth filter. The output of the filter is sampled at the symbol rate and these samples are fed into a VA in an exact manner as in the case of the SRRC receiver. The structure of this receiver is shown in Fig. 8. Note that the SPIK receiver does not have the inherent phase tracking problem (due to TWTA) as in the case of the SRRC signal. Also *more optimum* receivers can be constructed with some increase in computational complexity.

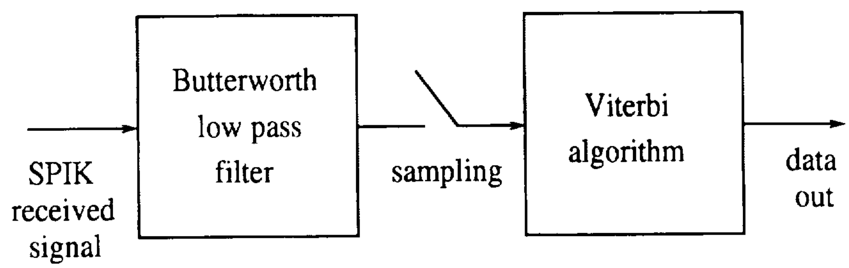

Figure 8: One possible SPIK receiver structure

4 Results and Discussion

4.1 Spectral Properties

The spectral properties of SRRC and SPIK modulated signals are found to be not affected by the CCSDS encoding. In other words, the spectral properties of uncoded SRRC and SPIK signals are the same as those of CCSDS encoded SRRC and SPIK signals respectively. The normalized power spectral density of the SRRC modulated waveforms is shown in Fig. 9 for a roll off factor $\alpha = 0.35$ when a linear amplifier is employed. The spectra of SPIK modulated signals is also shown. It is observed that, in terms of spectral performance, SRRC outperforms SPIK in linear channels.

Figure 10 shows the spectra for SRRC and SPIK when a TWT amplifier is used. It is seen that SPIK outperforms the SRRC waveform in terms of spectral efficiency. The TWT operates at 0 dB IBO and the bit rate R_b refers to the uncoded bit rate. Figure 11 shows similar results for SRRC filter with a roll-off factor of 0.5. In order to improve the spectral efficiency, the SRRC signal must be operated with more IBO. In Fig. 12, the SRRC signal is operated with 7 dB IBO. An SSPA model with 0 dB IBO is considered in Fig. 13. It is observed that the effect of SSPA is not as degrading as that of the TWTA. However, SPIK still performs much better than SRRC in terms of spectral efficiency.

4.2 Bit Error Rate Performance

The BER performance of CCSDS encoded SRRC and SPIK signals in linear channels is shown in Fig. 14. In the SRRC approach, the received signal is first matched filtered with an SRRC waveform and these samples are used in the Viterbi algorihm. In the case of SPIK, the received signal is low pass filtered and then the samples are presented to the Viterbi algorithm. This figure shows that, in linear channels, SPIK loses by about 2.4 dB compared to SRRC. Thus, SRRC is both bandwidth and power efficient in linear channels.

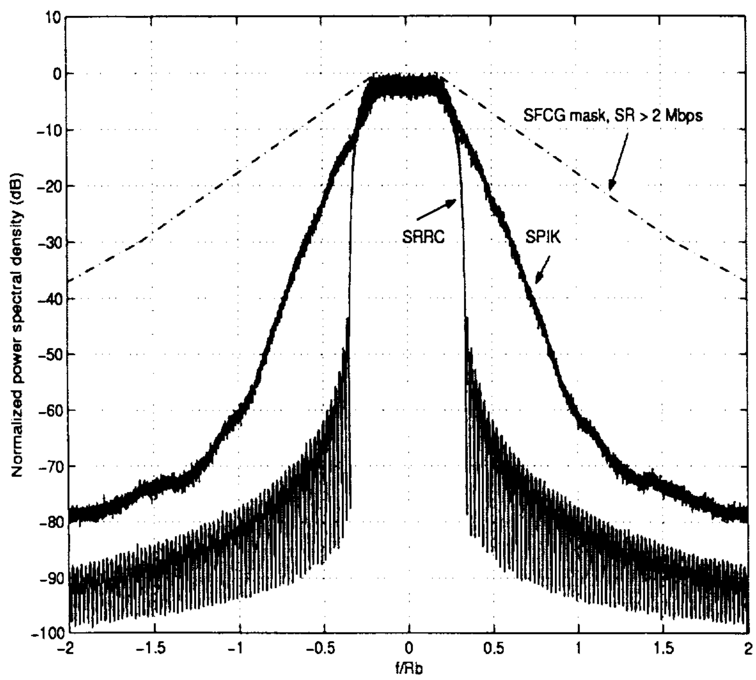

Figure 9: Spectra of SRRC (roll-off factor=0.35) and SPIK signals in linear channels

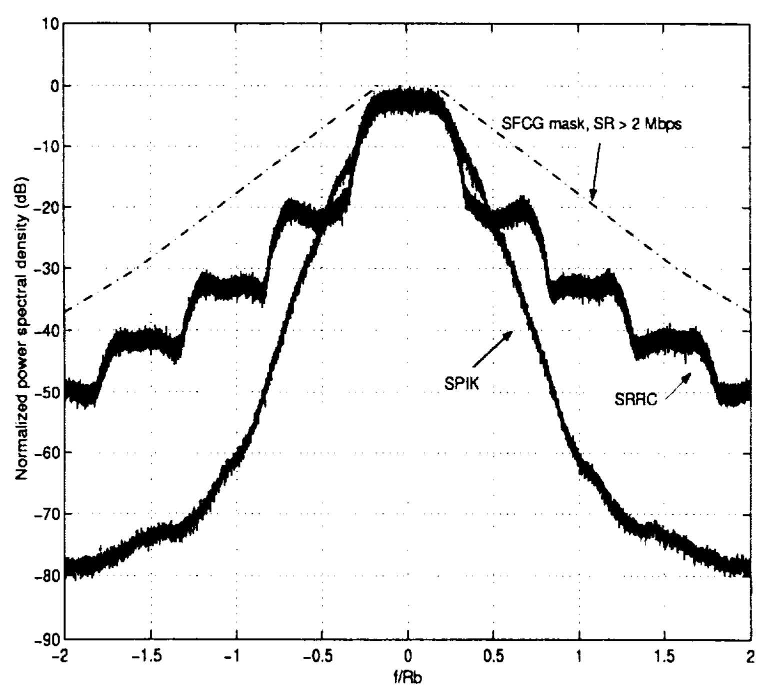

Figure 10: Spectra of SRRC (roll-off factor=0.35) and SPIK signals with a TWTA (0 dB IBO)

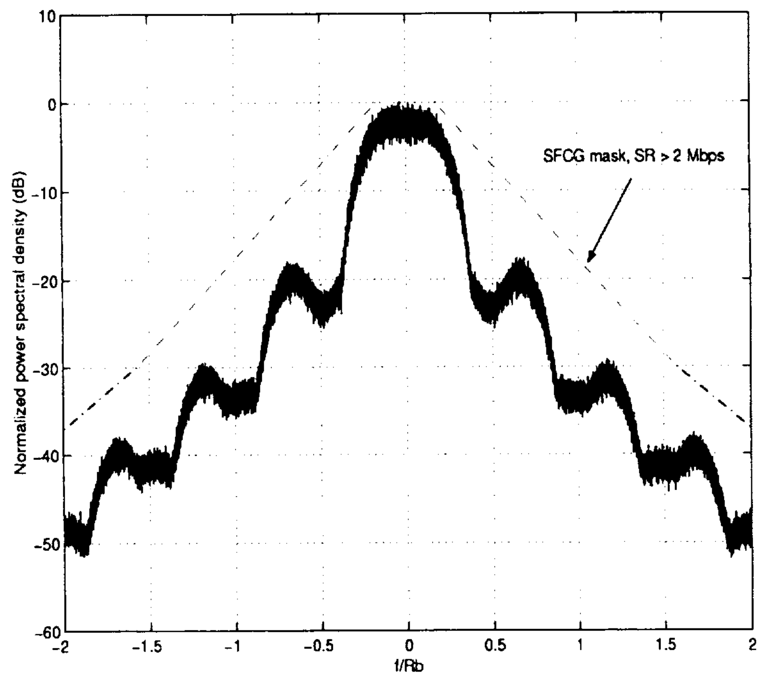

Figure 11: Spectra of SRRC with a TWTA (0 dB IBO) for roll-off factor=0.5

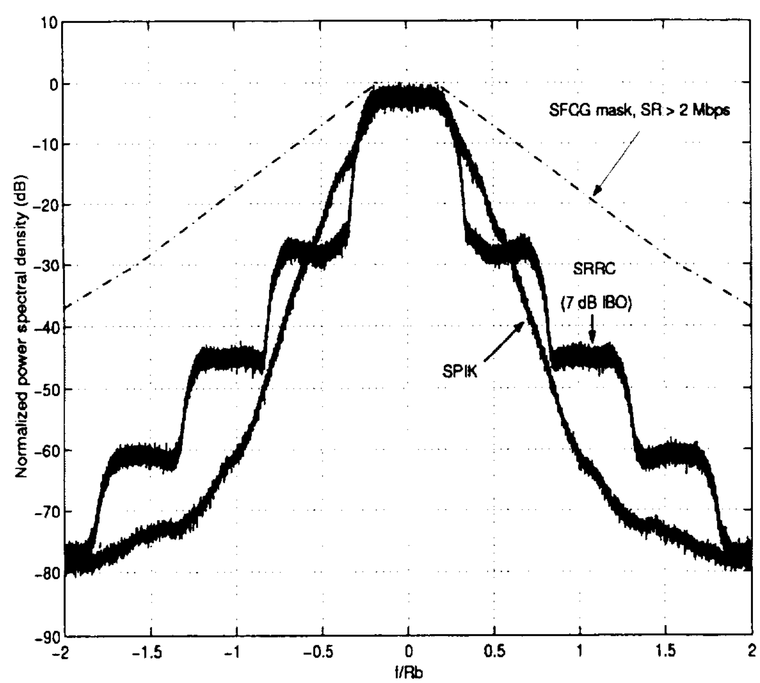

Figure 12: Spectra of SRRC (roll-off factor =0.35) and SPIK signals with a TWTA (7 dB IBO)

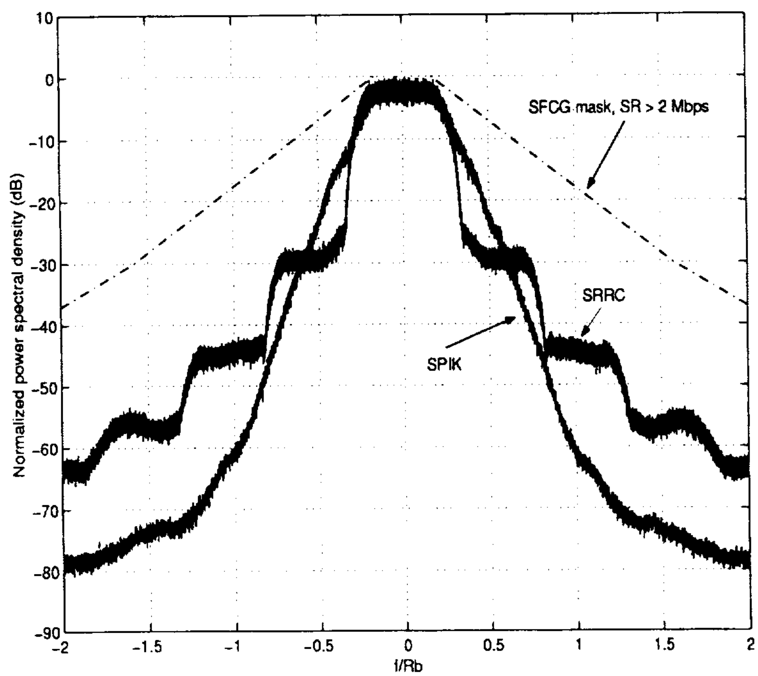

Figure 13: Spectra of SRRC (roll-off factor=0.35) and SPIK signals with an SSPA (0 dB IBO)

In Fig. 15, we show the performance degradation of SRRC when a TWTA is used with a 0 dB IBO. Note that the SNR (E_b/N_o) is measured at the input to the demodulator. The figure shows that, at a BER of 10$^-$4, SRRC loses nearly 0.5 dB due to distortions caused by the TWTA. However, to see the overall effects, we consider the total degradation (TD), defined as

$$\text{TD (dB)} = \left.\frac{E_b}{N_o}\right|_{\text{NLA}} \text{(dB)} - \left.\frac{E_b}{N_o}\right|_{\text{LA}} \text{(dB)} + \text{OBO (dB)}$$

where $\frac{E_b}{N_o}|_{\text{NLA}}$ and $\frac{E_b}{N_o}|_{\text{LA}}$ are the $\frac{E_b}{N_o}$ values required for a given BER with nonlinear and linear amplifiers respectively. The output backoff (OBO) represents the difference in dB between the maximum output power and the effective available output power. Our results show a TD of nearly 0.9 dB (=0.5 dB + 0.4 dB) for SRRC signals at a BER of 10^{-4}, where the OBO value of 0.4 dB is obtained by directly calculating the available output power during simulation.

Figure 16 shows the performance degradation of SRRC when an SSPA is used with a 0 dB IBO. The figure shows that, at a BER of 10^{-4}, SRRC loses about 0.25 dB due to distortions caused by the SSPA. The TD is found to be about 0.75 dB (=0.25 dB + 0.5 dB).

A performance comparison of SRRC and SPIK in TWTA environment with 0 dB IBO is shown in Fig. 17. It is observed that the performance gap between SRRC and SPIK at a BER of 10^{-4} is about 1.8 dB in this case. In order to take the overall effects of the TWT into account, we define 'relative degradation' (RD) of modulation type 1 with respect to modulation type 2 as

$$\text{RD (dB)} = \left.\frac{E_b}{N_o}\right|_1 \text{(dB)} - \left.\frac{E_b}{N_o}\right|_2 \text{(dB)} + \text{OBO}_1\text{(dB)} - \text{OBO}_2\text{(dB)}$$

where $\frac{E_b}{N_o}|_i$, $i = 1, 2$, represents the $\frac{E_b}{N_o}$ value required by modulation type i for a given BER and OBO_i is the corresponding output backoff. We find that the relative degradation of SPIK with respect to SRRC is about 1.4 dB.

There are two important points to keep in mind in this study.

- In the case of the SRRC method, we have assumed that the phase distortion caused by the TWTA is completely tracked and eliminated. Thus, the SRRC results provide a lower bound, since in practice, this phase distortion can cause further degradation in performance. Since this degradation depends on the phase tracking method employed, we leave it for future study. In the case of SPIK signals, the phase distortion remains constant due to the constant envelope property of the signal and therefore, can be completely removed.

- More optimal detectors can be implemented for SPIK signals, and such optimal detectors can improve the performance of SPIK. In the case of SRRC, more optimal detector implementation is much more complicated, since the TWTA signal distorts the pulse shape. More optimal detectors should reduce the performance gap between SRRC and SPIK even further.

From the above discussion, we can state that, in a TWTA environment, the BER performance of SPIK may be close to, or even better than, the BER performance of SRRC. Moreover, SPIK has much better bandwidth efficiency. Therefore, SPIK may have an overall advantage over SRRC in TWT channels. However, the final conclusion depends on the study of the optimal structure for SPIK and phase tracking performance of SRRC signals.

Figure 18 shows the BER performance comparison for SRRC and SPIK signals when an SSPA is used. In this case, the performance gap between the two signals is about 2 dB. In the case of the SSPA model, for the same input power to the SSPA, the output power of SPIK is about 0.5 dB higher than SRRC. The relative degradation is thus about 1.5 dB. Note that the effect of using a more optimal receiver structure for SPIK needs to be seen.

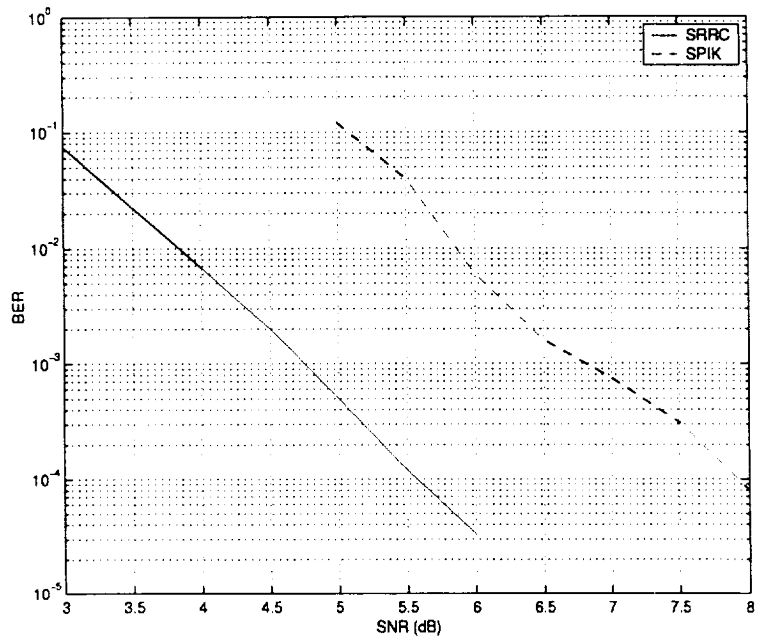

Figure 14: BER performance of SRRC and SPIK in linear channels

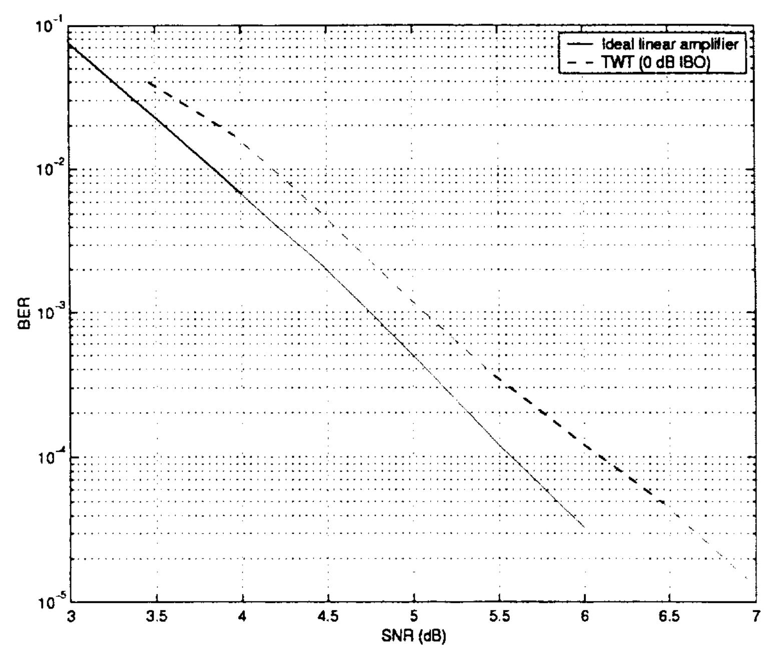

Figure 15: BER performance of SRRC when a TWT is used

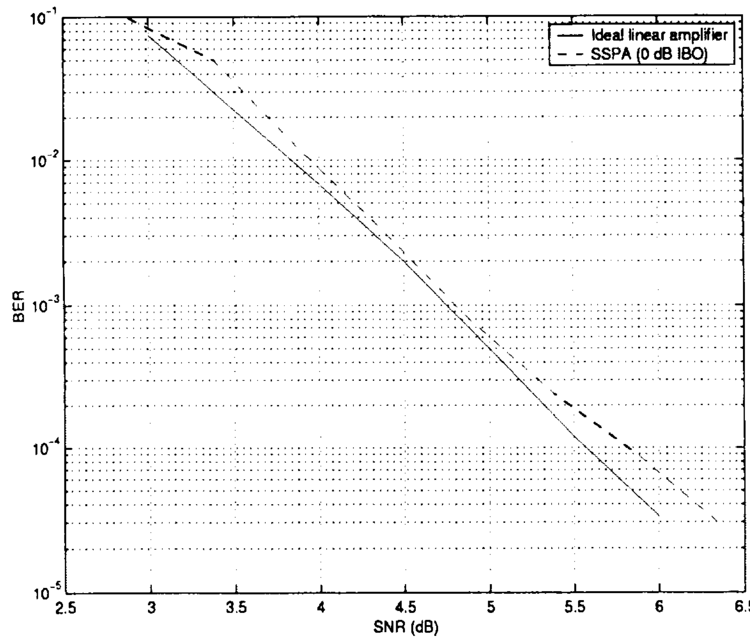

Figure 16: BER performance of SRRC when an SSPA is used

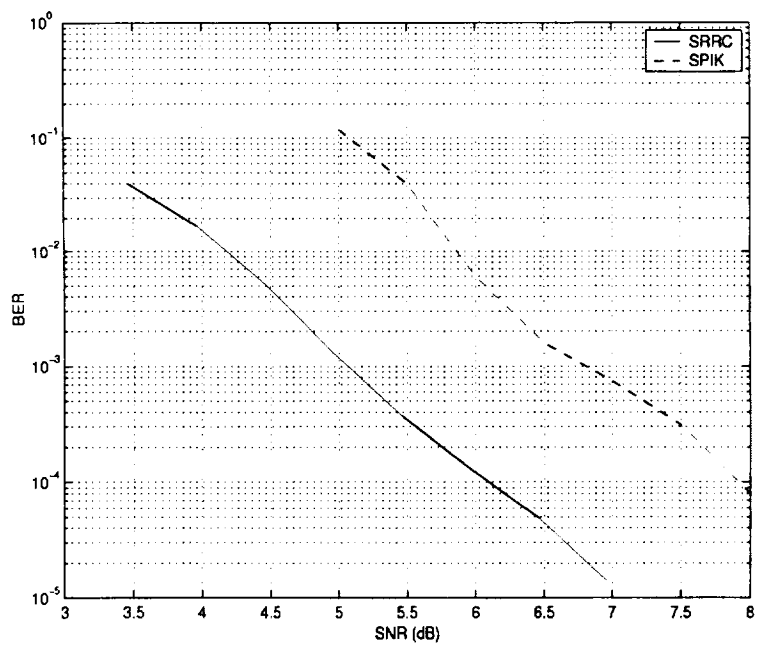

Figure 17: BER performance of SRRC and SPIK when a TWT is used

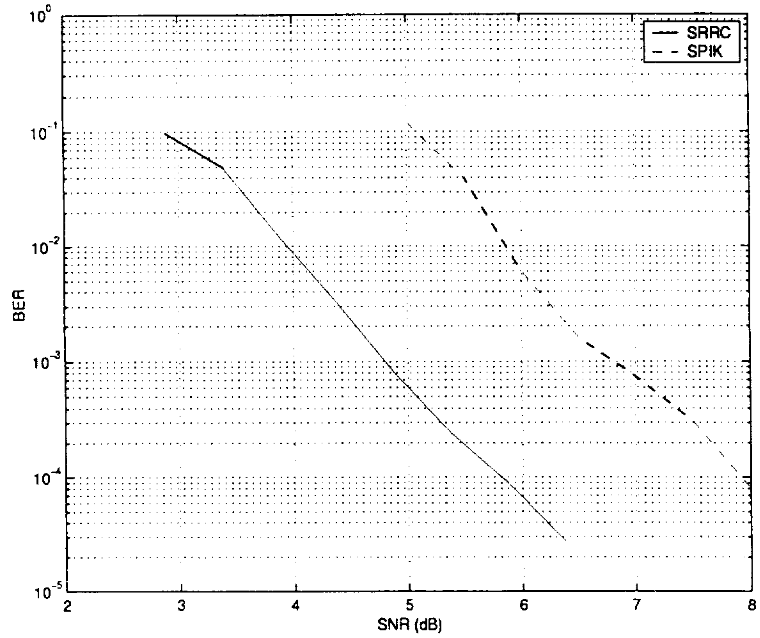

Figure 18: BER performance of SRRC and SPIK when an SSPA is used

5 Conclusions

CCSDS has recommended 8-dimensional 8 PSK TCM for near-earth missions. The modulation uses SRRC pulses. The important steps of the CCSDS scheme include conversion of serial data into parallel form, differential encoding, convolutional encoding, constellation mapping, and filtering the 8-PSK symbols using the square root raised cosine (SRRC) pulses. The last step, namely the filtering of the 8 PSK symbols using SRRC pulses, significantly affects the bandwidth of the signal. If a nonlinear power amplifier is used, the SRRC filtered signal creates spectral regrowth. This report investigates a technique, called the smooth phase interpolated keying (SPIK), to explore the possibility of obtaining better spectral and power efficiencies.

In order to understand the spectral properties better, we first examine the effects of the CCSDS encoder. Our study finds that the CCSDS encoder does not affect the spectral shape of the SRRC filtered signal or the SPIK signal. When a nonlinear traveling wave tube amplifier (TWTA) is used, the spectral performance of the SRRC signal degrades significantly while the spectral performance of SPIK remains unaffected. The degrading effect of a nonlinear solid state power amplifier (SSPA) on SRRC is found to be less than that due a nonlinear TWTA. However, in both cases, the spectral performance of the SRRC modulated signal is worse than that of the SPIK signal. The spectral performance of SPIK signals can be improved even further by employing additional filtering. This requires further study.

The bit error rate (BER) performance of linearly amplified SRRC signal is about 2.5 dB better than that of the SPIK signal when both the receivers use algorithms of similar complexity. In a nonlinear TWTA environment, the SRRC signal requires accurate phase tracking since the TWTA introduces additional phase distortion. This problem does not arise with a SPIK signal due to its constant envelope property. In a nonlinear amplifier environment, the SRRC method loses nearly 1 dB in the bit error rate performance. The SPIK signal does not lose any performance. Thus the performance gap between SRRC and SPIK reduces. The BER performance of SPIK can be improved even further by using a more optimal receiver. However, a similar optimal receiver implementation for SRRC is very complex since the nonlinear amplifier distorts the pulse shape. This requires further investigation and is not covered in this report.

6 Recommendations

The study shows that SRRC modulation and SPIK can both be used with CCSDS 8 dimensional 8 PSK trellis coded modulation. Both provide good spectral and power efficiencies, and satisfy the spectral mask requirements of the Space Frequency Co-ordination Group's (SFCG's) recommendation 17-2R1. The spectral performance of the SRRC technique is poorer than SPIK when a nonlinear amplifier is used. Thus SPIK may cause less interference to neighboring channels and is more promising for future systems that require stringent bandwidth control. The spectral performance of SPIK signals can be improved even further by employing additional filtering. However, this is not investigated in this report and requires further investigation. The BER performance of SPIK is about 2.5 dB inferior to SRRC in linear channels. In the case of nonlinear channels, the performance of SRRC degrades by nearly 1 dB, and thus the performance gap between SRRC and SPIK decreases. Moreover, optimal receivers can be designed for SPIK signals in order to narrow down this gap even further. A preliminary study, not presented in this report, shows such a promise. It needs to be seen whether the bit error rate performance of SPIK can be made better than, or at least very close to, SRRC signals. This remains a topic for future research.

7 References

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List of Symbols, Abbreviations, and Acronyms

AM/AM	Amplitude Modulation to Amplitude Modulation
AM/PM	Amplitude Modulation to Phase Modulation
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
dB	decibel
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobiles
IBO	Input backoff
ISI	Intersymbol Interference
LPF	Low Pass Filter
MF	Matched Filter
NLA	Nonlinear Amplifier
OBO	Output backoff
OQPSK	Offset Quadrature Phase Shift Keying
PSK	Phase Shift Keying
RD	Relative Degradation
SFCG	Space Frequency Coordination Group
SNR	Signal-to-Noise Ratio
SPIK	Smooth Phase Interpolated Keying
SRRC	Square Root Raised Cosine
SSPA	Solid State Power Amplifier
TCM	Trellis Coded Modulation
TD	Total Degradation
TWT	Traveling Wave Tube
VA	Viterbi Algorithm