Modelling and Digital Compensation of the Satellite Transponder Non-linearities

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STATEMENT OF CANDIDATE

I, Cameron Croker, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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Date: 04/09/2017

ABSTRACT

This thesis will seek to explore the area of linearization of power amplifiers and how these devices' nonlinearities affect the signals that are processed through their networks. Further, this thesis will aim to explore the literature that surrounds this field and discuss the implications of this research on the practical aspects the of research study in question. This field of research has many implications and sections of this thesis will seek to explore the outcomes of the endeavour on future developments in this arena.

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Chapter 1 Introduction

1.1 Introduction

In the field of telecommunications engineering there consists systems which involve nonlinear components. These components are often causes of reduced communication system effectiveness due to affecting phase and amplitude distortion. The goal of this project was to produce a form of linearisation which was capable of reducing the effects of these nonlinearities on the satellite communications channel, specifically, this project aimed to reduce these effects in the power amplifiers present in satellite transceivers.

The field of satellite communications is a field of ongoing study as it provides the means for remote area communication where physical data lines cannot reach, global or cross continental secured communications channels, mobile communications and near space and deep space applications. These applications capabilities enable systems that deliver functionalities that are novel and draw on the substantial technologies developed in this field. These satellite communications networks are always evolving, and this field has room for developments in a variety of different directions. One such area of development is in the improvement of satellite communications systems effectiveness based on improvements to the onboard satellite communications hardware and in the onboard signal processing schemes.

Nonlinearities are large contributing factors towards bottlenecks in satellite communications systems. Nonlinearities require that components be driven at levels below their theoretical maximum and directly result in power amplifier inefficiencies in component usage. These nonlinearities lead to reduced transmit power and increased complexity of systems in order to deliver the satellite communications systems operating requirements.

The nonlinearities present in power amplifiers are a major source of the distortions which are inherent in satellite transponders. One of the many parameters used to characterise the functional capabilities satellite transponders is often the gain delivered by the power amplifier. These components are often driven lower than their theoretical maximum and as such have an operational power that is below the functional the capacity of the component. This difference between capacity and operating power is known as the output power back-off, (opbo), and is directly due to the presence of nonlinearities.

The aim of this project and thesis is to approach the problem of satellite transponders through an examination of the linearisation techniques available to the power amplifier component. The type of linearisation that will be investigated is adaptive digital predistortion, which will be discussed in subsequent chapters. A brief summary will be given here.

Adaptive digital predistortion is a type of linearisation which involves the collection of the output of the power amplifier, performing error estimation over the output in order to define the characteristic coefficients and using digital techniques to introduce inverse nonlinearities which can counteract the effect of the nonlinearities present. This technique results in a high level of linearisation and increased power amplifier efficiency.

This thesis will aim to provide an outline of the current work regarding the nonlinearities in the power amplifier and their characteristics and will aim to investigate the current paradigms available regarding linearisation and their effects on satellite transponder communication. Further, it will aim to put forward practical, implementable predistortion systems with an aim for future development in the improvement of satellite communications systems design.

Chapter 2

Background and Related Work

2.1 Literature Review

Effective nonlinear representation

The Saleh model is a commonly used model for understanding and characterising nonlinearities in nonlinear systems [1]. This model has been investigated thoroughly in the literature and has been shown to be accurate in narrow band applications. These models have been shown to track accurately with the physical systems we are simulating. This model is expressed as a two-parameter model in both Amplitude-phase and In-phase-quadrature representation.

The Saleh amplitude(A(r))-phase(Φ(r)) model representation can be expressed as the following

$$A(r) = \frac{\alpha_a r}{(1 + \beta_a r^2)}$$

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

These two expressions can be shown to effectively model the nonlinear products of nonlinear systems. This form of the expression separates AM-AM distortions and AM-PM distortions and considers them as separate products for the purposes of conceptualization these components of distortion separately.

The In-phase-quadrature variant is capable of expressing these components as in-phase components and Quadrature components. One of the results of this variant is a useful analytical property which will be discussed later in this chapter. The In-phase-quadrature model can be expressed as follows

$$A(r) = \frac{\alpha_p r}{(1 + \beta_p r^2)}$$

$$\Phi(r) = \frac{\alpha_q r^3}{(1 + \beta_q r^2)^2}$$

[where r is the amplitude of the input function, α_a α_q β_a β_q is the parameter of amplifier dimension] This form of the expression has the useful property which can be expressed as allowing the quadrature components to be expressed as a function of the in-phase components. Analytically this can be represented as

$$Q(r) = -\frac{\delta P(r)}{\delta \beta_p}\bigg|_{\alpha_p \to \alpha_q, \beta_p \to \beta_q}$$

the expressions discussed here are effective at characterising the nonlinearities present in nonlinear power amplifier components and provides an excellent basis from which to simulate our project within the context of a MATLAB/Simulink program. As an aside, often nonlinear systems can be discussed in the context of with memory effects and as those without. It has been shown that in narrow band contexts memoryless nonlinearities are sufficient at accurately representing nonlinear systems.

Adaptive digital Predistortion

Adaptive digital predistortion is both functional and effective as a means of linearisation as it is cost effective and functional, capable of improving nonlinear systems by a significant amount. These systems operate under the premise that one can generate a look-up style implementation of coefficients in system memory which involve characterising the input-output transfer function and use this to compensate for the nonlinear errors present in the power amplifier. This process generates an inverse nonlinearities vector [2] which can then be applied to the input signal to rectify the spectral expansions and in-band distortions applied by the power amplifier, effectively reducing error at the decision maker at the receiver side due to corrections to the constellation points. This is achieved by first routing the input signal through the predistortion coefficient generation module via the lineariser module which generates the outputs for this error coefficient vector which are then applied to the input effectively applying nonlinearization that is inverse to the nonlinearities present in the power amplifier. This predistorter input is then fed into the power amplifier to generate a linearized version of the output signal.

Methods of Error estimation

The method of linearisation we seek to implement is based on a Least Mean Square (LMS) implementation which is a form of error estimation. This form of estimation has complexity and output capabilities which meet the requirements of our proposed system. The LMS component error correction in a time that is within both the time and complexity requirements of this system.

Another method of error estimation that will be used is Recursive Predictor Error Method. This method has the benefit of being faster in estimating errors and as such reduces the overall bit error rate of the output of the power amplifier system. This method however, has greater complexity and is harder to implement in practice as it requires more components. In practice however, the benefits of increased speed of convergence to the error estimate makes it a useful option to examine.

This method of nonlinearization performs the function of generating a map of coefficients from the nonlinear characteristic distortions to the original linear input [3]. The resultant coefficient vector is then used to provide an accurate transfer of the input to a predistorter version which is then fed through the HPA. The effect of this process results in distortion correction at the HPA output. This can be understood as returning the constellation points of the output signal to their original input position resulting in more accurate signal recognition at the receiver (4).

The adaptive digital predistortion algorithm that will be expressed by this system will utilize both a Least Mean Square algorithm as well as a recursive predictor error method algorithm. Linearisation of this form can be implemented in many ways including using Least Mean Square (LMS), Recursive Least Square (RLS) (5), Least Mean Square Newton (LMSN), Recursive Predictor Error Method (RPEM) among many other implementations. These differing implementations have different characteristics in terms of computational time and complexity. Furthermore, the accuracy of these systems differs in terms of the overall effectiveness in the linearisation of power amplifiers. The implementations most often used are based on the Least Mean Square algorithm, as these tend to provide the necessary accuracy within an acceptable computational time. This approach will be the one that will be used in this simulation.

2.2 Simulations Background

Currently this project requires the simulation of a satellite transceiver that will be pursued by modelling and simulating those components as those detailed in the project plan and will aim to simulate those components such as a modulator and a demodulator for the simulated modulations schemes of QAM and PSK. These components which will provide the necessary signal to be amplified and include a signal generator to generate the message signal driving this system. This system will also include an additive white gaussian noise generator which will simulate channel interference and amplify using a Saleh nonlinearity model amplifier completing the power amplifier model.

The main simulation engine will be MATLAB and Simulink which will provide the environment for the simulation. This environment hosts powerful processing capabilities which will provide the means to drive the proposed system and generate functional modelled system simulations which will in turn provide the results necessary to complete this research. The main component that will be simulated will be drawn from the Simulink library which will be modified to suit our purposes. The components will be combined in such a way as to produce an accurate model as based on the theory and as defined in the previous chapter.

The main component that will be driving the simulations theoretical basis will be the memoryless nonlinearity component which provides the means to generate accurate nonlinearity coefficients. This component will allow us to derive an accurate power amplifier model. This accurate HPA model will allow us to in turn devise an accurate adaptive digital predistortion scheme which will form the main outcome of this research.

The adaptive digital predistortion scheme will provide powerful mechanisms to linearize the nonlinear system in question. In order to approach this system systematically a static system will first be modelled as a comparison system to quantify the overall improvements provided by an adaptive system. This system will rely on the generation of coefficients using an initial input to the system as a training signal. This will generate a static transfer vector algorithmically which will then be used to linearize the HPA.

The adaptive algorithm will be implemented using a coefficient module which utilizes a learning architecture in order to generate coefficients using a Least Mean Square algorithm implementation. This system is implemented using a Simulink harness to simulate the various components associated with this method of estimation. As well as the various components associated with this system as a whole.

The error estimation is implemented using various mathematical components such as complex conjugation, a gain component, a multiplier, adder and delay mask. These components allow us to generate an accurate Least Mean Square estimation implementation which converges on an accurate output predistortion coefficient estimation. This algorithm will allow us to generate an accurate predistortion algorithm for error measurement as well as drives the digital predistortion linearisation module.

Chapter 3

Simulations and Analysis

3.1 Introduction

The expressions discussed in the above chapters can be implemented using a Simulink component known as the memoryless nonlinearities component. This component is able to provide the mapping from AM-AM distortion parameters and AM-PM distortion parameters accurately (to within a double representation). This will allow us to provide the requisite nonlinearities as defined by our model of a power amplifier.

The simulation that will be pursued here involves the construction of several blocks which will effectively model the signal processing component of a satellite transceiver as well as the channel noise and receive end of the earth receive base station. The simulated system includes the capabilities to generate an adequate message signal which provides a signal of necessary complexity. The simulation will also include components which collectively provide the function of linearisation. These components were developed utilizing an adaptive implementation which includes a least mean square implementation. Further, the system includes a component which provides the function of amplification in a similar way such as those given by a physical HPA. Capable of delivering both the gain increase as necessary, and also the nonlinearities characteristic of the component in practice, simulating an accurate representation of a HPA.

The signal generation component includes the capability to provide a signal to be amplified. This includes the capability to generate random integers as well as modulate them in such a way as to simulate the associated real-world applications. This includes the capability to perform PSK and QAM modulation. These forms of modulation and the performance of the lineariser on the bit error rate were measured in the presence of additive white gaussian noise. As such, this simulation accurately represents the physical system under investigation to a high degree of accuracy.

The power amplifier was constructed utilizing a gain component a complex digital filter and a Saleh memoryless nonlinearity component. These components come together to form an accurate model of real-world power amplifiers and allows us to study the effects of these nonlinearities on the transmit signal. The effects of these nonlinearities were observed using constellation diagram mapping, frequency-power representation and BER measurement, in order to better understand the effects of linearisation, nonlinearities and channel effects on the signal.

The linearisation of this system was provided by a component formed of an adaptive digital predistorter component and a coefficient calculation component. The adaptive digital component multiplies the input signal by coefficients generating the predistorted signal. The coefficient generation component takes the power amplifier input and output and performs a Least Mean Square operation over the signal input which produces a mean error function and the coefficients to the digital predistorter component. This component reverses the order of the power amplifier output and feed it through the LMS component to producing the digital predistortion coefficients and the mean error measurements.

3.2 Results

The results of the simulation as undertaken by this projected are presented in this section. This includes a presentation of the models that were defined in the outline of this project, in the project scope document and the project plan document. The results of this work are discussed in terms of the bit error rate and the effects on the spectrum of the signal and the constellation diagram clustering. These methods of quantifying the benefits of this system will allow us to better understand the effects of linearisation on the amplifier and the results of these benefits on the communications channel.

The effect of linearisation on this system result in overall reduction of nonlinearities in the out of band region by approximately 7dB. The overall BER for this system is in the range of less than 1.83×10^{-5} over a sample size of 2.804×10^{5} which is as expected with the theory as it suggests a high level of linearity. The constellation diagrams also suggest the linearity of this system is within theory. The constellation points show no presence of phase distortions or amplitude distortions in the signal.

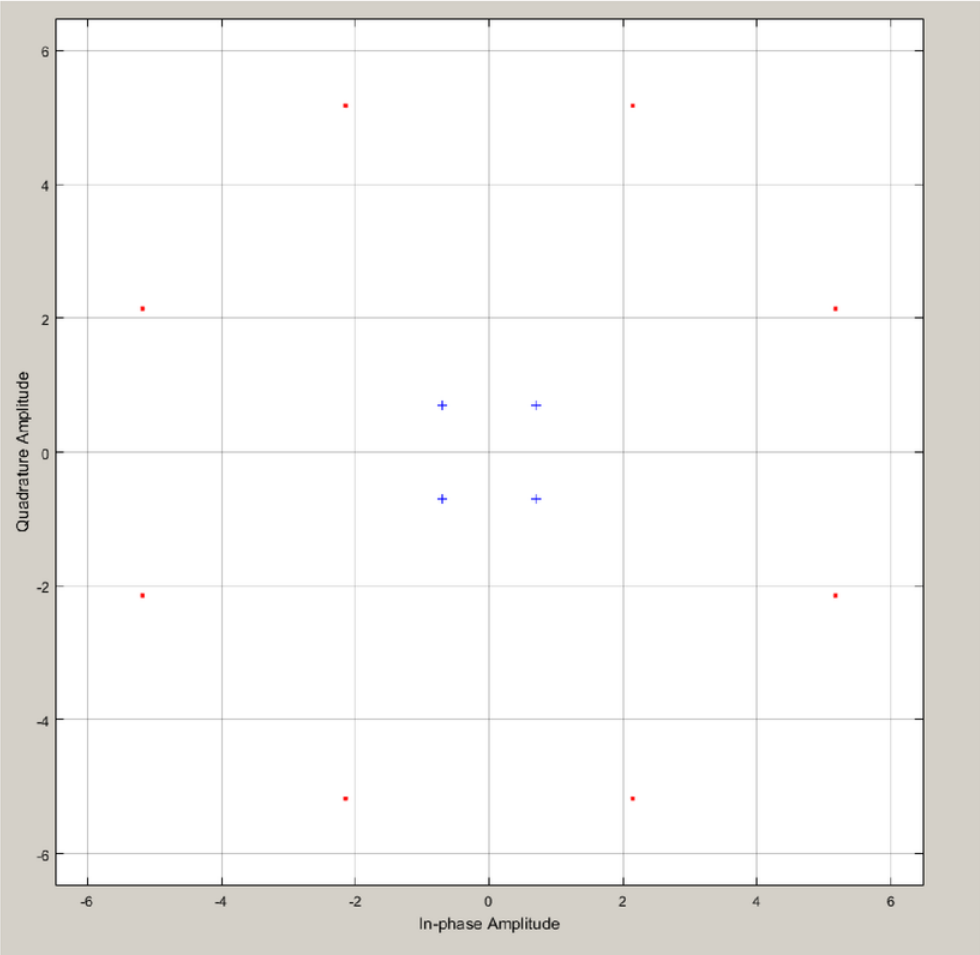


Figure 1: Constellation diagram of the input signal

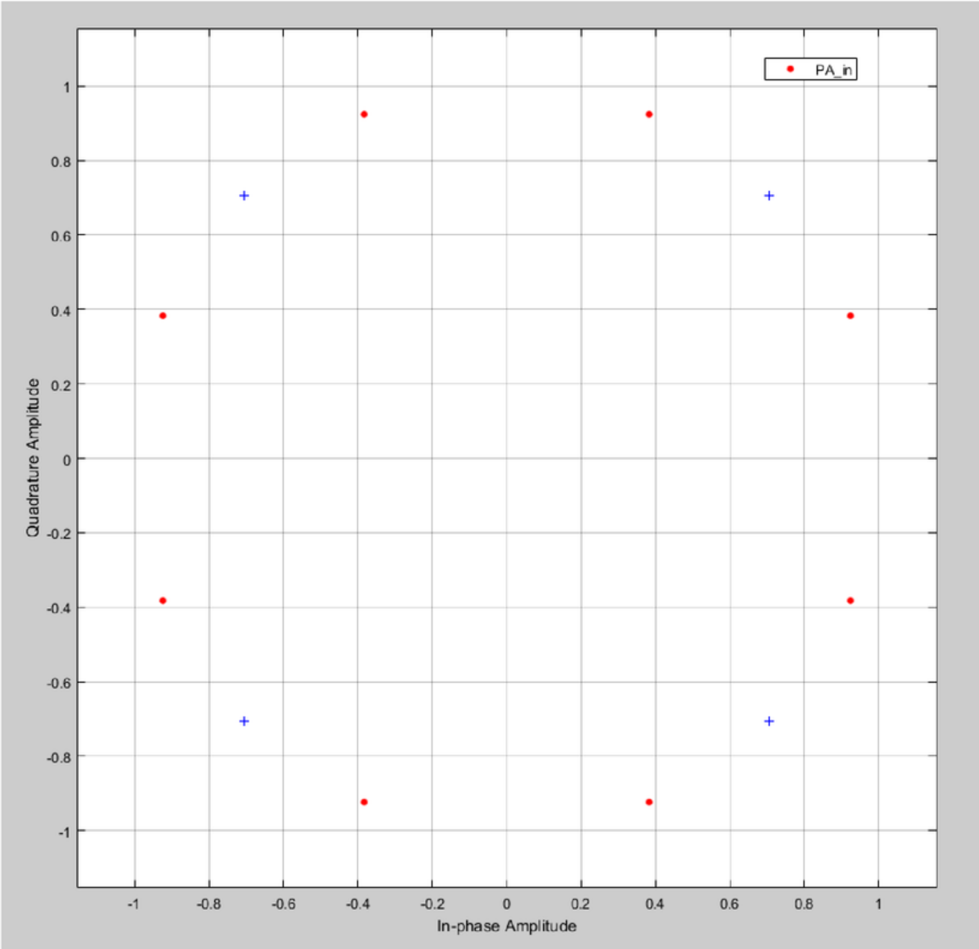
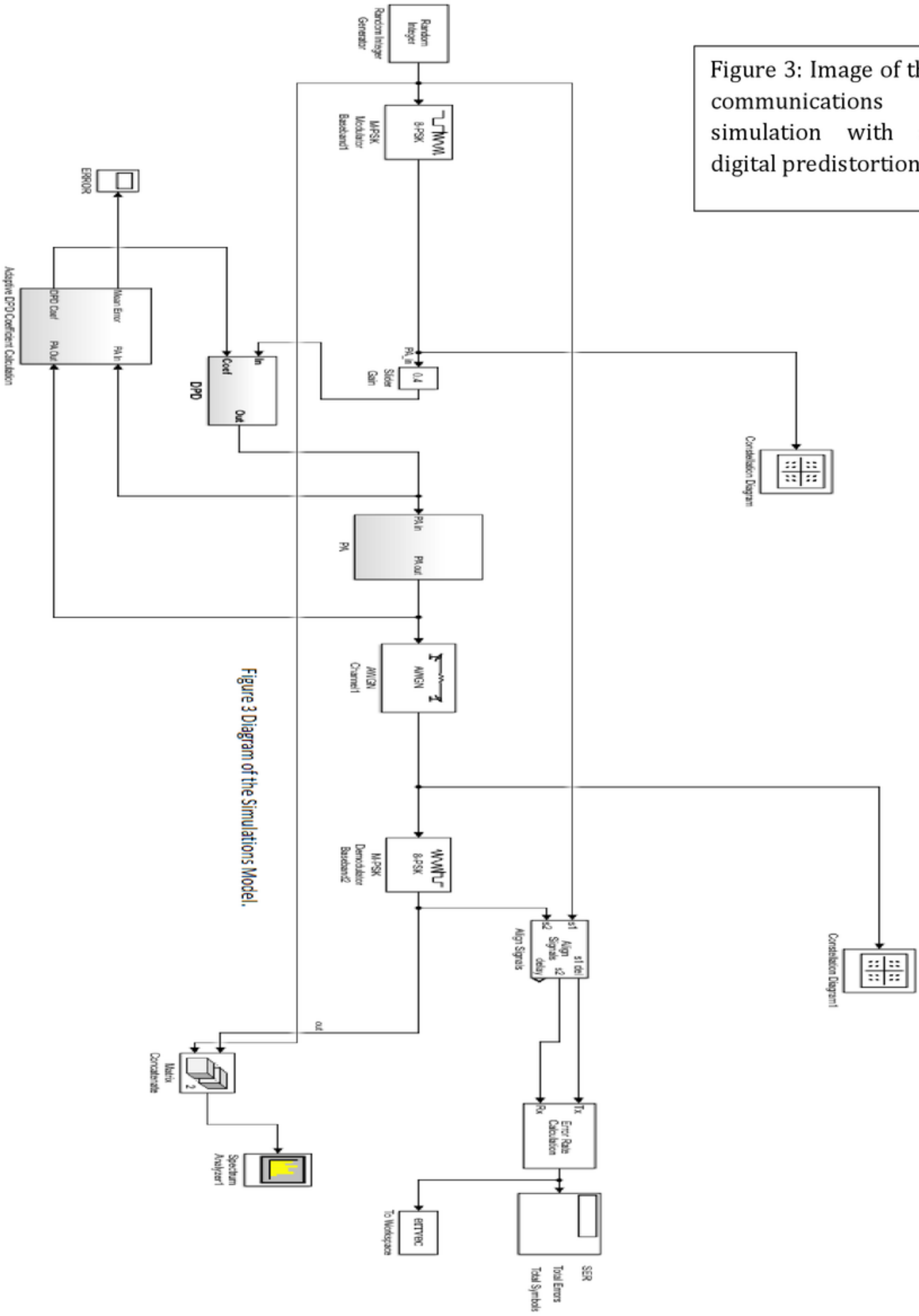
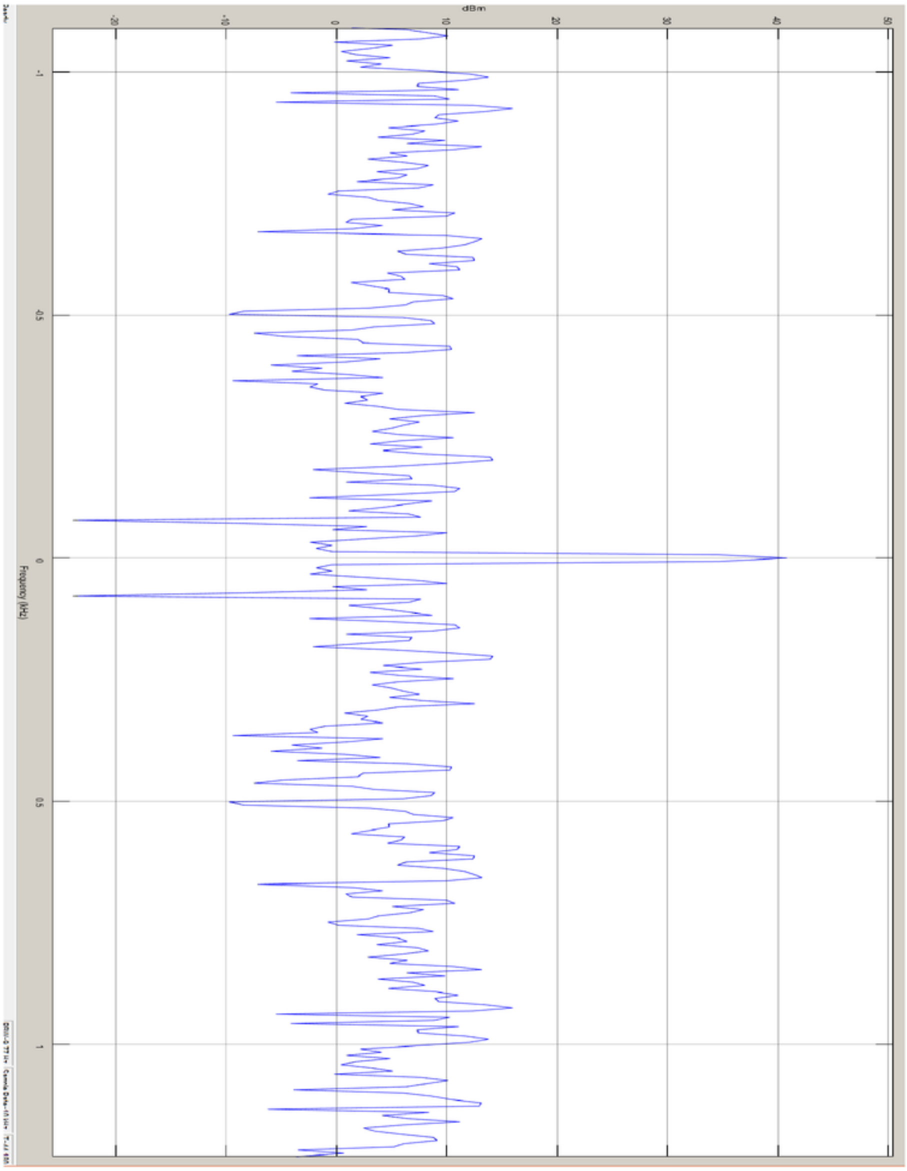


Figure 2: constellation diagram of the output of the M-PSK signal

Figure 3: Image of the entire communications channel simulation with adaptive digital predistortion.





4: Signal spectrum of the output of linearised system with the signal spectrum of the input signal Pre-Amplification

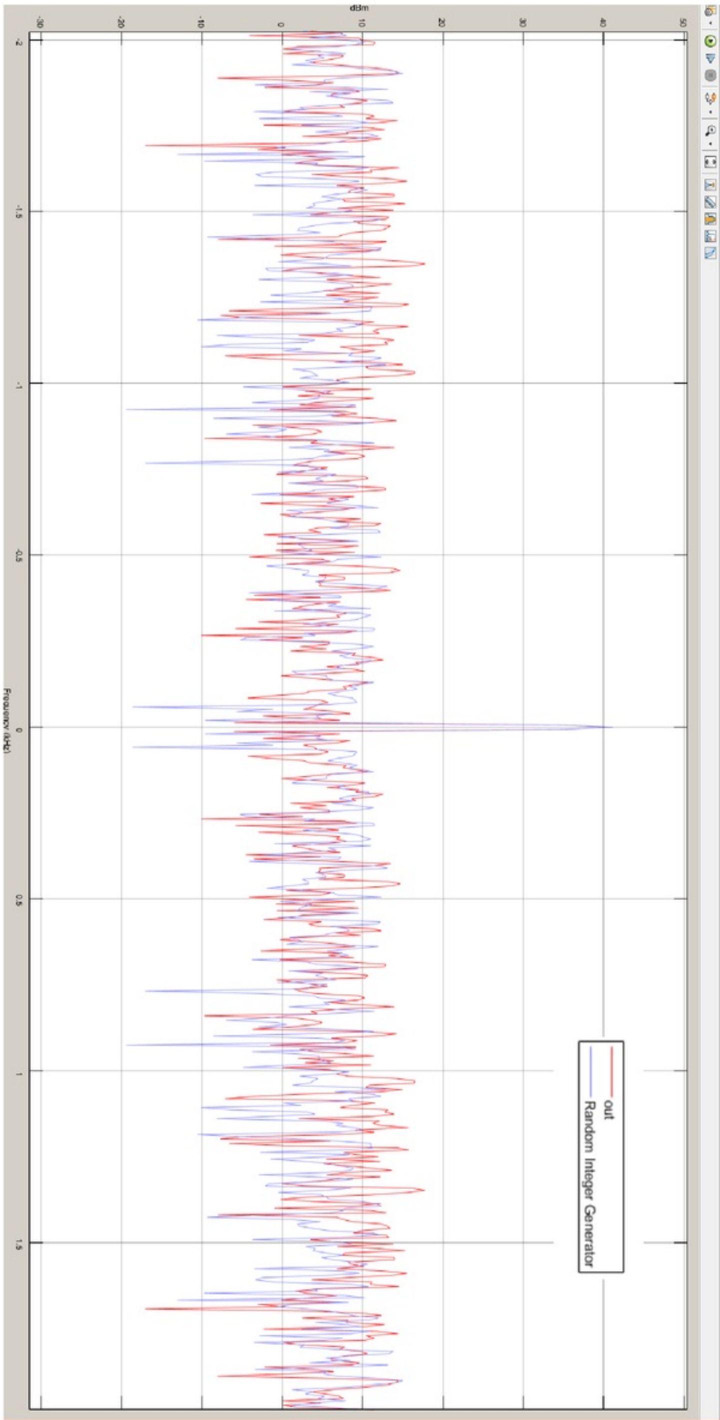


Figure 5: signal spectrum of the output of the nonlinear system. Yellow is the signal spectrum of the output signal.

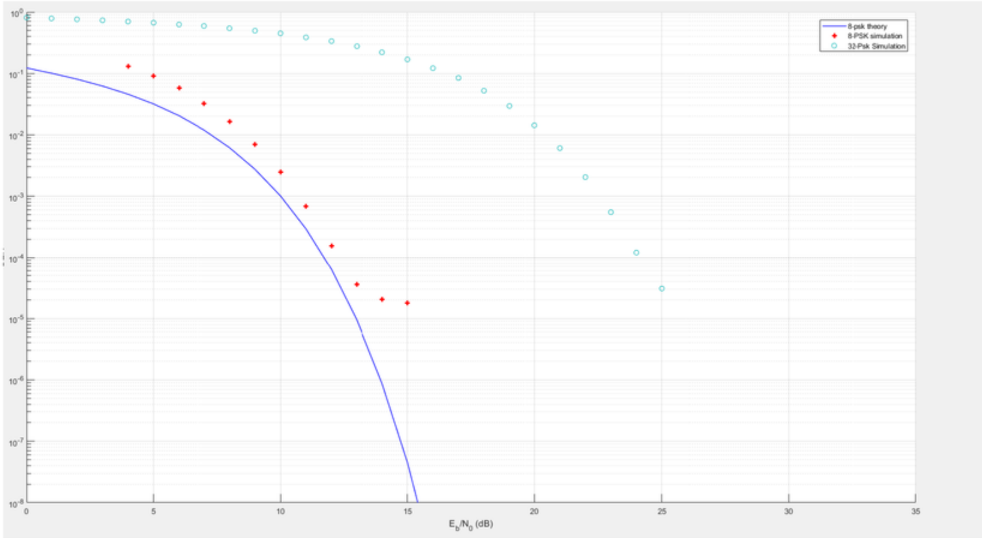


Figure 6. Image of the Bit Error Rate plot of the simulation for 8-psk from theory and from simulation, as well as simulated 32-psk.

Chapter 4

Conclusions and Future Work

4.1 Conclusions

The work that was completed with this project was the functional and effective implementation of satellite communications transponder simulations including transmit and receive. This system is able to provide an effective solution to the problem studied, namely, increase the data bandwidths in communication satellite channel by reducing the nonlinearities associated with the use of power amplifiers. This project allowed us to study an effective satellite communications system that provided the kinds of communications that are required as outlined by the project requirements document. The fulfilment of these outcomes allow for the future provision of the kinds of data rates necessary for future satellite communications technology development.

This system was practical, in that its implementation was readily realisable and potentially capable of performing at a high level of accuracy, making it an interesting candidate for study. It had a relatively simple design and the implementation that emerged from the project was robust. The necessity for this system is that there was a space for it in the satellite communication field as there is always a greater need for high efficiency components in satellite communications.

4.2 Future work

One of the main reasons this model was created was for the introduction of higher order modulation schemes in satellite communications channels. These higher order modulation schemes are useful as they allow for greater data rates and bandwidths in the satellite communications channel. The effects of these amplification improvements coupled with the introduction of higher order modulation schemes allow for more advanced systems and techniques when considering future applications.

Future work in this area will be improvements to the algorithms and the implementation of faster error estimation. This will result in power amplifiers that are more reactive to their environment and the channel variables. These improvements will allow for the implementation of future devices capable of supporting more advanced signal processing, more intelligent applications and greater overall robustness of signals in the presence of channel constraints and channel interference factors.

Chapter 5

Abbreviations

AWGN	Additive White Gaussian Noise
BC	Broadcast Channel
BS	Base Station
CSI	Channel State Information
CSIR	Channel State Information at Receiver
CSIT	Channel State Information at Transmitter
dB	Decibels
DPC	Dirty Paper Coding
GS	Gram-Schmidt
RVQ	Random Vector Quantisation
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
MISO	Multiple Input Single Output

SIMO	Single Input Multiple Output
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combining
QoS	Quality of Service
TDD	Time Division Duplex
FDD	Frequency Division Duplex
ZF	Zero-Forcing
ZFBF	Zero-Forcing Beamforming
ZMCSCG	Zero Mean Circularly Symmetric Complex Gaussian

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