FOUR-DIMENSIONAL Q²PSK MODULATION AND CODING FOR MOBILE DIGITAL COMMUNICATION

CHAPTER 1

INTRODUCTION

In this chapter an overview of the research and a formulation of the problem that is addressed in this study are given. Importantly, most of this chapter is concerned with the extensive literature study which was carried out. This is followed by a section in which the contributions of this study are highlighted and placed in perspective. The chapter closes with a schematic representation and a written outline of the dissertation.

1.1 INTRODUCTION AND OVERVIEW

In its basic electrical sense, the term *communication* refers to the sending, receiving and processing of information by electric means. As such, it started with *wire telegraphy* perfected by Samuel Morse in the eighteen-forties, followed by the development of *telephony*, conceived by Alexander Graham Bell some decades later, and *radio* at the beginning of this century [1]. *Radio communications*, made possible by the invention of the triode tube, was greatly stimulated by the work done during World Wars I and II. Then, after a long pause, *digital radio* (i.e., digital communications by radio) experienced a renaissance in the early 1970s. Renewed interest in microwave radio as a transmission medium for digital communications was largely due to the introduction of digital switching at that time. It subsequently became even more widely used and refined through the invention and use of the transistor, integrated circuits and other semiconductor devices [2]. More recently, the use of satellites has made radio communications even more widespread [3, 4].

Truly, the invention of the telegraph and telephone in the 19th century was the first steps towards shattering the barriers of space and time in communication between individuals. The second step was the successful deployment of radio communications. To date, however, the location barrier has not been completely surmounted: people are less tied to telephone sets or "fixed wireline" equipment for communication. With an annual growth rate of 40% per year, wireless (mobile) communication is the fastest growing sector of the communications sector [5]. The ultimate goal of

Personal Communication Services (PCS) is to provide instant communication between individuals located anywhere in the world, and at any time. In mobile digital radio communications, however, both the available frequency spectrum and the transmitter power are limited. In order to cope with the ever-increasing amount of data traffic which has to be accommodated in the already overcrowded electromagnetic spectrum and the demand for more efficient transmission, improved modulation techniques are needed. This increasing demand for digital transmission channels in the radio frequency band creates a challenging problem for the communications engineer.

In recent years, the emphasis has been placed on the development of signalling strategies for digital communication that conserve both available power and bandwidth. An example of a spectrally efficient modulation scheme is $\pi/4$-QPSK, which has been selected as the standard for the new U.S. digital cellular system. This nonconstant envelope linear modulation scheme has a higher spectral efficiency (1.62 $bits/s/Hz$) than constant envelope modulation schemes such as MSK, GMSK (0.83 $bits/s/Hz$ and digital FM (0.67 $bits/s/Hz$) previously employed in mobile radio systems [6, 7, 8, 9, 10]. Due to the increasing demand for mobile communication services more efficient modulation techniques than $\pi/4$-QPSK need to be investigated for future mobile communication systems.

The foregoing discussion is the motivation for the research carried out at the University of Pretoria, the main objective being to investigate spectrally efficient signalling strategies to be employed in mobile digital communication systems. With this objective in mind, a multidimensional QPSK modulation scheme, known as Quadrature-Quadrature Phase-Shift Keying (Q^2PSK) [11, 12] has been selected as a platform. This scheme has a theoretical bandwidth efficiency of 4.0 $bits/s/Hz$ and an elegant signal structure which facilitates the incorporation of sophisticated forward error correction strategies.

The dissertation objectives can be summarised as follows:

- Design and realisation of a mobile digital Q^2PSK communication system.
- Design and simulation of sophisticated error correction strategies.
- Performance evaluation under typical mobile fading V/UHF channel conditions.

Within the framework of the objectives, this research study has set out to investigate the design, implementation and evaluation of a digital Q^2PSK modem for application to mobile communication on typical V/UHF channels. Key aspects, such as digital modulation and demodulation, block signalling format and synchronisation, including carrier tracking strategies, are addressed. In addition, the design and implementation of sophisticated error correction strategies, including classical convolutional codes, trellis codes and multiple trellis codes are considered. Although, most of the concepts of multidimensional modulation and particularly four-dimensional signalling are not new, the utilisation, actual implementation and evaluation of these techniques in the digital communication environment are of crucial importance. The final objective of the dissertation is to evaluate the performance of the digital Q^2PSK (uncoded as well as trellis coded) communication system under typical static and mobile fading channel conditions.

1.2 LITERATURE SURVEY

In this section attention is focused on a literature survey of published technical material concerning the two main topics of this dissertation; namely multidimensional modulation and the application of coding to these modulation schemes.

1.2.1 Multidimensional modulation

Motivation for the use of multidimensional signals for digital transmission dates back to the work of Shannon [13]. Shannon showed that it is theoretically possible to have error-free transmission over a noisy channel if the transmission rate does not exceed the capacity of the channel. In this classical paper Shannon related the information capacity of a communication channel to bandwidth and Signal-to-Noise Ratio (SNR), as follows:

$$C = \frac{1}{2}\log_2\left(1 + \frac{P_s}{P_n}\right) \tag{1.1}$$

where C represents the number of error-free bits per second that can be transmitted in a per hertz Hz bandwidth, P_s is the received average signal power and P_n the average noise power added to the signal. Any communication system attempts to transmit the maximum number of information bits in the minimum time and at the minimum expense of signal energy [14]. In his celebrated analysis of the limiting performance available in digital communication over a given channel, Shannon also recognised that the performance of a signal constellation used to transmit digital information over a Additive White Gaussian Noise (AWGN) channel can be improved by increasing N, the dimensionality of the signal set used for transmission. In particular, as the dimensionality grows to infinity, the performance tends to an upper limit defined as the capacity of the channel in (1.1) [13, 15].

Heuristically, as the number of dimensions grows more space becomes available to accommodate the signals, and hence the Euclidean distance between signal points increases. In turn, a greater distance between signal points means (at least for high-enough signal-to-noise ratios) a smaller error probability. The price paid for an improvement in performance when the dimensionality is increased is essentially the increase in complexity of the modulator and demodulator.

1.2.1.1 Four-Dimensional Signalling

The notion for Four-Dimensional (4D) signalling was first considered by Wilson and Sleeper [16], employing a technique known as "frequency-reuse". Frequency-reuse is a technique which utilises two spatially-orthogonal electric field polarisations for communicating on the same carrier frequency to double the apparent spectral capacity of a satellite communication system. Provided that the two fields can be kept orthogonal (admittedly a problem on land mobile channels due to depolarisation), the spectrum efficiency is twice that of a non-frequency strategy, and the energy efficiency is exactly that of a single channel at the same energy requirement level. A typical application would perform Quadrature Phase-Shift Keying (QPSK) on each polarisation, providing a theoretical spectral efficiency of 4.0 *bits/s/Hz*. Figure 1.1 illustrates the block diagram of such a modulator with Two-Dimensional (2D) polarisation and frequency-reuse, forming a 4D signalling scheme.

The 4D receiver employs quadrature carrier demodulation on each of the polarisations, followed by matched filtering and decision making. The problem with the foregoing scheme is that the space

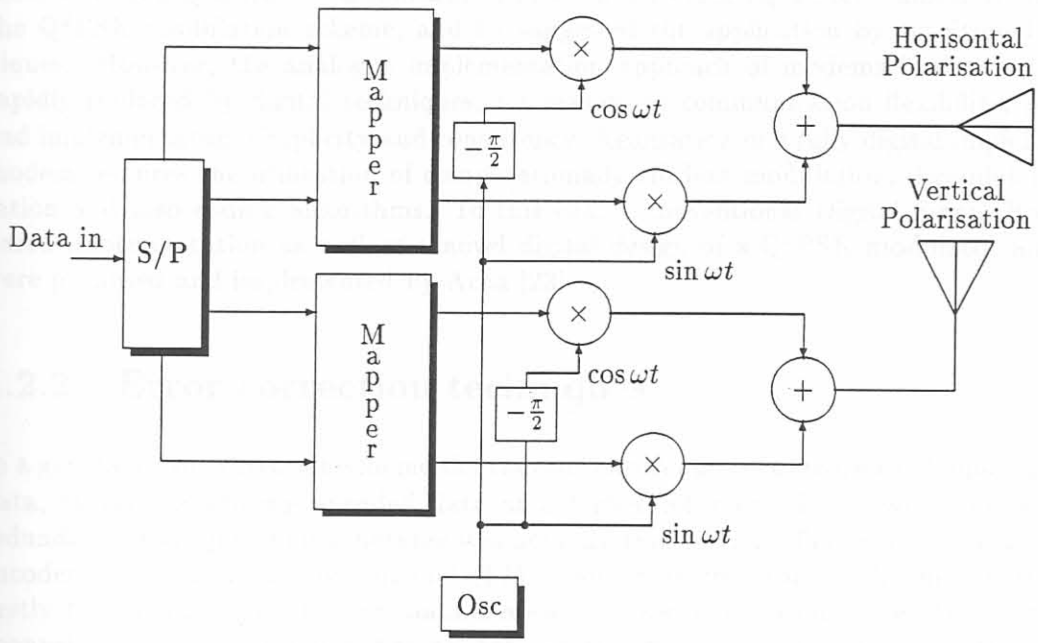

Figure 1.1: Modulator with 2D/Polarisation and frequency-reuse.

polarisation would be difficult, even impossible, when considering application to a land mobile communication scenario.

An overview of the current papers available on multidimensional modulations are summarised, with specific reference to 4D modulations: Uncoded Four-Dimensional (4D) signal sets were considered by Welti and Lee [17], Zetterberg and Brändström [18], Wilson et al. [19], and Biglieri and Elia [20]. Welti-Lee codes are essentially subsets or translations of the lattice consisting of the points in the 4D space whose integer components have an even sum. Zetterberg-Brändström designs are based on quaternary groups, and their signals are constrained to have an equal energy. Wilson *et al.* consider 4D signal sets based on subsets of lattice packings. Gersho and Lawrence [21] consider four- and eight-dimensional signal sets with two information bits per dimension. Their designs show a 1.2 to 2.4 *dB* gain in noise margin over conventional (two-dimensional) quadrature amplitude modulations.

1.2.1.2 Four-Dimensional Q^2PSK

A measure of spectrally efficient modulation lies in the notion of effective use of available space dimensions. This notion of effective use of available signal space, was considered by Saha [11, 12]. In Quadrature Phase-Shift Keying (QPSK) and Minimum Shift Keying (MSK), the symbol duration T_s is $2T_b$, where T_b is the bit interval of the incoming data stream. If one supposes that the channel is strictly bandlimited to $1/T_b$ on either side of the carrier, then the two-sided bandwidth occupancy is $W = 2/T_b$, and the number of available signal space dimensions is $T_sW = 4$ [22]. Only two of these dimensions or degrees of freedom are utilised in QPSK and MSK.

Saha observed the shortcomings of the existing modulation schemes in the utilisation of available signal space dimensions and proposed the development of the new class of digital modulation scheme named Quadrature-Quadrature Phase-Shift Keying (Q^2PSK). Saha developed the basis of the Q^2PSK modulation scheme, and he suggested the application by traditional analogue techniques. However, the analogue implementation approach of modems is out-dated and is being rapidly replaced by digital techniques, for reasons of communication flexibility, power efficiency, and implementation simplicity and consistency. Realisation of a fully digital implementation of the modem requires the utilisation of computationally efficient modulation, demodulation, synchronisation and also coding algorithms. To this end, a conventional Digital Signal Processing (DSP) based implementation as well as a novel digital design of a Q^2PSK modulator and demodulator were proposed and implemented by Acha [23].

1.2.2 Error correction techniques

In a general error correction scheme the *channel encoder* adds controlled *redundancy* to the message data, thereby producing encoded data at a higher bit rate. The *channel decoder* exploits the redundancy to decide which message was actually transmitted. The two main goals of the channel encoder, in a Land Mobile Channel (LMC) and Satellite Mobile Channel (SMC) scenario are firstly to minimise the effect of channel noise, and secondly to minimise the effects of the fading channel. That is, the number of errors between the channel encoder input and the channel decoder output must be minimised. The use of coding adds complexity to the system, especially for the implementation of the decoding operation at the receiver. Thus, the design trade-offs in the use of error-control coding in order to achieve acceptable error performance, are considerations of bandwidth and system complexity.

Coding techniques are generally divided into two main types: *block coding* and *convolutional coding* [24, 25]. Convolutional coding was first proposed by Elias for use over discrete memoryless channels. Its superior performance over block coding, for a given amount of system complexity, has gained its success in many communication systems. Although, at first the application of convolutional coding to bandlimited channels was not originally thought of as being practical. In 1967, Viterbi derived an error exponent for convolutional codes using an asymptotically optimum decoding algorithm, known as the Viterbi Algorithm (VA), which constitutes the basis of new coding techniques.

1.2.2.1 Combined Coding and Modulation

In classical digital communications systems, the functions of modulation and error correction were separated, but in 1974 Massey advocated the viewpoint of regarding channel coding and modulation as an entity [26]. This view was later pursued by Ungerboeck in the design of his well-known multi-level/phase convolutional codes with asymptotic coding gains of up to 6.0 *dB* [27, 28, 29]. Ungerboeck's originality was the use of an expanded signal constellation and a *set partitioning technique* to accommodate the redundant bits introduced by coding. This coding technique is nowadays known as Trellis Coded Modulation (TCM).

The advantages offered by Ungerboeck's technique is twofold: First high coding gains may be obtained and, secondly information rate is maintained without expanding the required bandwidth. Over the last 2 decades TCM has emerged as an efficient and reliable coding scheme used for data communication with the purpose of improving the reliability of a digital transmission system without increasing the transmitted power or the required bandwidth.

The definition of TCM given by Biglieri *et al.* [30] can be stated as follows:

> *The trellis code solution combines the choice of a higher-order modulation scheme with that of a convolutional code, while the receiver, instead of performing demodulation and decoding in two separate steps, combines the two operations into one.*

A different description of trellis codes was formulated by Calderbank and Mazo [31]. The description is known as the analytical description, where the trellis code is seen as a *sliding window* method of encoding a binary data stream as a sequence of real or complex numbers that are sent over the transmission channel. The main characteristics of the analytical description is that the codes may be described very simply, and strict bounds on performance can be obtained.

1.2.2.2 Design for AWGN channels

In the design of TCM schemes for the AWGN channel, the most significant parameter is the Euclidean distance of the code, which must be maximised in order to ensure an optimum code. It is known, that asymptotically, the error probability is upper- and lower-bounded by a function that decreases monotonically when the Minimum Squared Euclidean Distance (MSED), increases. The free Euclidean distance is thus the most significant single parameter useful for comparing TCM schemes employed for transmission over the AWGN when the Signal-to-Noise Ratio (SNR) is large enough [30].

In 1983, Fang claimed that an improved error performance was achieved by Four-Dimensional (4D) channel coding, with the expanded signal set similar to Ungerboeck's set partitioning method [32]. In a later publication, Biglieri analysed some of the codes developed by Ungerboeck on non-linear channels [33], where he showed that the codes were particularly attractive for application in the band-limited environment. In the same year Wei discovered the use of non-linear trellis codes, with the incorporation of a 90° invariant property which gives the coded system immunity against 90° phase jumps at the demodulator [34, 35]. Rate 3/4 convolutional coding for 16-PSK was analysed by Wilson [19], who demonstrated that trellis coded 16-PSK was preferable to trellis coded 16-Quadrature Amplitude Shift Keying (QASK) on non-linear satellite channels.

TCM systems traditionally used symmetric constellations, with uniformly spaced signal points. Symmetric systems are optimum for uncoded signals, but in a paper by Divsalar [36] it was shown that trellis codes with asymmetric constellation may offer a better performance than those with symmetric constellations on AWGN. Calderbank published a paper where new trellis codes based on lattices and cosets were presented [37]. A good review of TCM systems may be found in a paper of Benedetto [38], where theoretical aspects of the encoding process are investigated.

1.2.2.3 Design for Fading channels

All the references given in the foregoing section dealt with design and analysis of trellis codes for AWGN channels, where the parameter to be maximised is the Euclidean distance of the code. This criteria is valid for AWGN channels, however in practical channel other parameters do also have to be taken into account. There is presently a large amount of work being done on coding for fading channels.

The first papers concerned with the design and application of TCM for fading channels were published by Divsalar and Simon [39, 40, 36, 41, 42]. In these papers the authors established that depending on the Rician factor of the channel, the diversity of the code will be the parameter to be maximised rather than the Euclidean Distance (ED). Performance criteria for the set partitioning of trellis coded MPSK for fading channels are shown by Divsalar and Simon. In the same paper the authors suggest the use of Multiple TCM (MTCM), wherein more than one channel symbol is assigned to each trellis branch. The main conclusions of this work were that for the design of the multiple trellis codes for optimum performance on the fading channel, the length of the shortest Error Event Path (EEP) and the product of branch distances along that path must be maximised. It is noted that the latter design objectives differ from the design of TCM schemes for AWGN channels, where maximisation of the free Euclidean distance of the code is the primary objective.

Other coding techniques for fading channels have been reported by Farrell [43] and Zehavi [44]. In his paper Farrell summarises the basic methods for combating fading with TCM systems. In a very recent paper by Zehavi, an alternative to the method for MPSK proposed by Divsalar and Simon, is presented. The approach is based on a convolutional code followed by bit interleavers, yielding a better coding gain over Rayleigh channels compared to when MTCM is employed.

An interesting paper of trellis codes for Frequency-Phase Modulated (FPM) signals was presented by Peryalwar [45], who showed that the optimum set partitioning of trellis coded FPM signals for fading channels also provides asymptotically optimum performance on AWGN channels.

1.2.3 Trellis codes for Q^2PSK

In this section the most important references, which dealt specifically with the design of trellis codes for Q^2PSK are given. It is surprising that only a few publications by Saha and Acha were found. In his first paper Saha proposed 7/8 rate trellis codes on the Q^2PSK signal space [46]. In this paper coding gains of 2.43 dB and 5.45 dB were calculated. In his second paper dealing with trellis coded Q^2PSK signals, Saha presented four main types of codes [47]. Analysis of these codes have shown that they are catastrophic. That is, if no redundant information is introduced it is not possible to obtain any coding gain. The first code presented by Saha, called rate unity, does not expand the original set and does not introduce any coding information in the signal. For the second code, being a 3/4 rate code, Saha proposed the utilisation of an 8 point constellation, which will not allow any redundant information to be introduced.

Different trellis codes for Q^2PSK have been developed by Acha. Trellis codes for AWGN channels were developed and evaluated in [48]. Four different types of trellis codes were designed. Rotationally invariant trellis codes have been designed for Q^2PSK signals by using multidimensional coding and double multi-level Convolutional Codes over Ring Modulo-8 (CCRM8). In the same paper half-rate constant envelope codes for Q^2PSK signals and double Ungerboeck codes for 8-PSK were presented and evaluated [48, 49].

1.3 DISSERTATION ORGANISATION

Figure 1.2 contains a schematical representation of this dissertation. The general background and topic of this study, as well as an overview of the relevant papers in the literature are presented in this chapter. The rest of the dissertation is divided into three parts following the main objectives. In the first part, Chapters 2 to 4, a theoretical analysis and the application of four-dimensional Q^2PSK to mobile digital communication are presented. In the second part, Chapters 5 and 6, the design and application of different trellis codes to the digital Q^2PSK modem is presented. Part III concentrates on the performance evaluation results, and the dissertation summary and conclusions. The original work of this study is presented in Chapters 4 to 6, and also in Chapter 7, containing a multitude of simulation results. Finally, four appendices are included at the end of the dissertation.

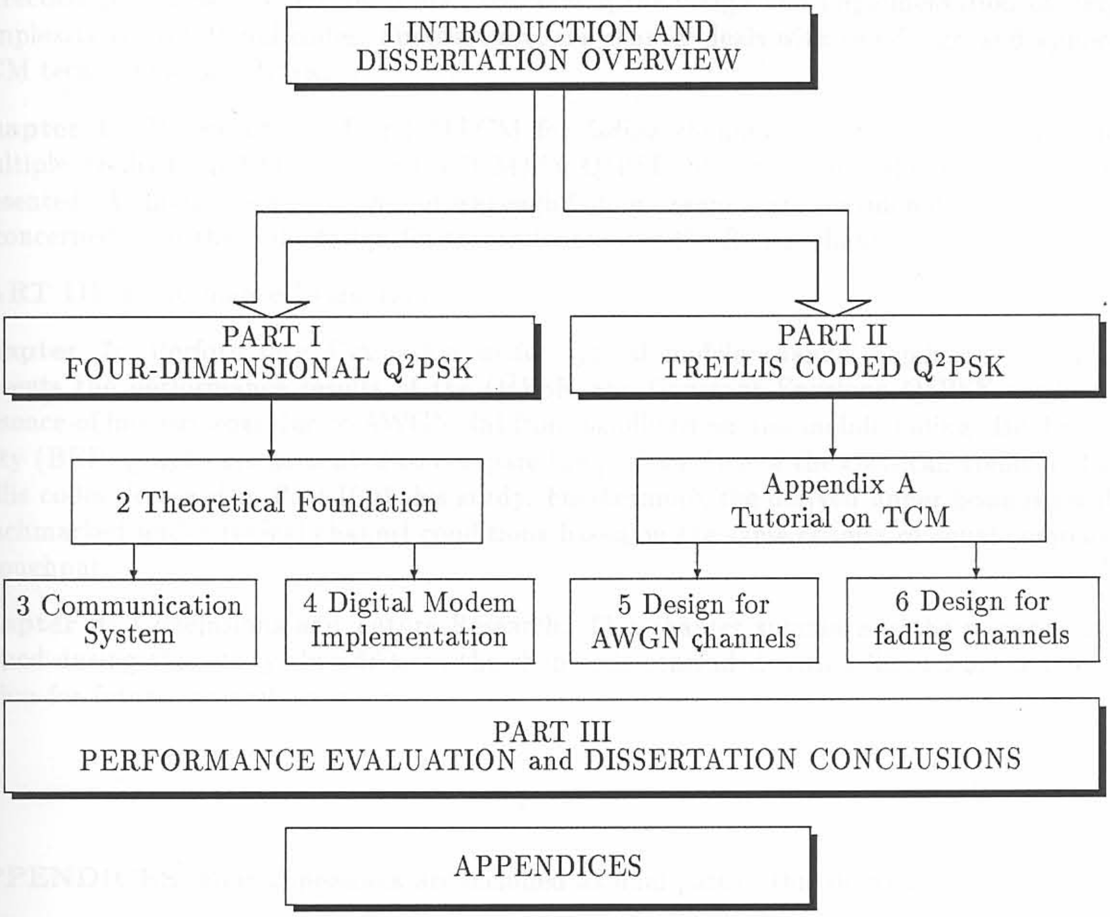

Figure 1.2: Dissertation organisation.

The dissertation is outlined as follows:

PART I: Four-Dimensional Q^2PSK — Theory and Application to mobile digital communication.

Chapter 2: Theoretical Foundation: In this chapter the concepts of four-dimensional signalling are considered. Furthermore, investigations into the constraints imposed by finite bandwidth and energy on the dimensionality and capacity of Q^2PSK are carried out.

Chapter 3: Communication System Concepts: This chapter is concerned with the introduction of the general architecture of the communication system under investigation. It is devoted to the study of the communication environment, including the channel model and link budget analysis. The chapter is concluded with a summary of the channel and modem specifications.

Chapter 4: Digital Q^2PSK Modulation, Demodulation and Synchronisation: In this chapter detail is presented concerning the design and implementation of the Q^2PSK modulation and demodulation processes.

PART II: Trellis Coding with application to Q^2PSK.

Chapter 5: Design for AWGN channels. This chapter is concerned with the design of trellis codes for AWGN channels, with specific reference to the application of classical and TCM forward error correction techniques to Q^2PSK. Detail concerning the design and implementation of simple low-complexity convolutional codes. Furthermore, the chapter deals with the design and application of TCM techniques for Q^2PSK.

Chapter 6: Design of TCM and MTCM for fading channels. In this chapter, the design of Multiple-Trellis Coded Modulation (MTCM) for Q^2PSK when transmitted over a fading channel is presented. Although, both Rician and Rayleigh fading channels are considered, most of this section is concerned with the code design for transmission over the Rician channel.

PART III: Performance Evaluation.

Chapter 7: Performance Evaluation under typical mobile channel conditions: This chapter presents the performance results of the Q^2PSK and Constant Envelope Q^2PSK modems in the presence of impairments due to AWGN, ISI from bandlimiting and mobile fading. Bit Error Probability (BEP) graphs are presented to compare the performance of the classical, trellis and multiple trellis codes designed in Part II of this study. Furthermore, the derived upper bounds on BEP are benchmarked under typical channel conditions based on the same criteria of equal complexity and throughput.

Chapter 8: Conclusions and Future Research: This chapter summarises the research work performed during this study. In addition, the chapter is concluded with a discussion and recommendation for future research avenues.

APPENDICES: Four appendices are included as final part of this dissertation.

Appendix A: Tutorial on TCM: This appendix presents a tutorial on the theory of TCM required in Part II of the dissertation, concerned with trellis code design for Q^2PSK. Specifically, the general concepts of trellis coded modulation, including the fundamentals, presentation, decoding and evaluation are discussed.

Appendix B: Code design — Utility software. This appendix presents the utility software developed in the design of trellis coded systems. The evaluation of the coefficients of the analytical description and the establishment of d_{free} are the two main tasks in the design procedure that must be carried out. The Calderbank—Mazo analytical presentation of TCM and MTCM is discussed. The general concepts and software developed to derive the analytical presentation are presented.

Furthermore, the software for evaluation of the minimum free Euclidean distance, d_{free} is discussed, based on the computational algorithm by Mulligan and Wilson.

Appendix C: Chan—Norton Algebraic algorithm. In this appendix the algebraic algorithm proposed by Chan and Norton for generating the transfer function, $T(D)$ of a trellis encoder is presented.

Appendix D: Set-partitioning for Q^2PSK/MTCM code design. In this appendix the complete partitioned Q^2PSK/MTCM subsets evaluated in Chapter 6 are given, for code cardinality of 16 and 8, respectively.