CHAPTER ONE

INTRODUCTION

> *"...we are very close to practical achievement of the performance that Shannon promised nearly* 50 *years ago. Is it therefore time to say 'Problem Solved' and move on to other things? I doubt it. Observe how much of this progress has been achieved only recently - e.g. in trellis codes, group codes, Turbo Codes, algebraic geometry codes and precoding. I doubt that it has been fully digested. In particular, we are still far from a fundamental understanding of the new code construction and decoding methods that seem to be embodied in Turbo Codes, nor have we fully exploited the promise of multilevel codes and multistage decoding. Moreover, every two years the boundary between 'feasible' and 'infeasible' advances by another factor of two. Indeed, I believe that in* 30 *years we will look back with nostalgia at the current era and say: 'That was a golden age.'"* [1]
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ALTHOUGH the debate on the existence of biological evolution rages on between the religious and scientific communities, one aspect of the human condition that has evolved at an exponential rate during the 30000 year age of modern man, is communication. In the early post-neanderthal days of homo sapiens, unintelligible grunts and mumbling soon gave way to verbalised speech, eventually progressing into current day's thousands of distinct languages and dialects. Simplistic cave drawings, telling the life and history of our pre-historic ancestors, grew into written language on stone tablets and papyrus. In the process, complex pictographic representations of spoken languages, such as Egyptian hieroglyphics and the Chinese alphabet, were developed. However, it was not until the invention of the printing press in 1450 by *Johann Gutenberg* that the true power of written language was revealed, inaugurating the dawn of modern literacy and education.

The notion of communication over long expanses has intrigued the human race for millennia. Written language carrier systems, such as message runners and carrier pigeons, evolved into today's modern postal services, the Internet, email systems and *Short Message Service*s (SMS). Moreover, the ever-present need for long distance transmission of verbal and unwritten information gave rise to the first terrestrial and wireless communication systems, such as the Navaho Indian's smoke signal system.

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[1] *Source: Shannon Lecture on Code Performance and Complexity,* 1995

From such rudimentary long distance communication systems, modern day telegraphy and telephony were spawned. Undoubtedly, the fathers of modern day communication systems, such as *Alexander Graham Bell* and *Guglielmo Marconi*, could not have envisaged a global village, based on total wired and wireless connectivity, were information sources can be freely accessed and a long-distance verbal conversation initiated at the touch of a button.

Since the inception of the 7-layered *Open Standards Interface* (OSI) model for communication systems, research and development of wired and wireless communication systems have become a global effort, progressing at an astounding rate. Today, the first commercial *Global System for Mobile Communication* (GSM) systems are 10 years young, but already seem underpowered and antiquated when compared to the 3^{rd} *Generation* (3G) systems currently being rolled out worldwide. Nonetheless, it still remains to be seen whether communication systems will eventually develop up to the point that Captain James T. Kirk can flip open his shiny 23^{rd} century Star Fleet issue subspace communicator, which is capable of communicating across the expanses of the known universe, in order to command Scotty to get a battle-scared Enterprise space-worthy in a humanly impossible time-frame. There is, however, one unavoidable impediment plaguing the transmission quality and reliability of all past, present and future communication systems: Non-ideal transmission channels.

Intuitively, non-ideal communication channels will have a limited capacity to carry information. In the last century many researchers attempted to sufficiently describe this phenomenon, but it was not until *Shannon*'s groundbreaking 1948 paper [1], entitled *"A Mathematical Theory of Communications"*, that it was possible to calculate a quantitative measure for this capacity limit. In this paper, *Shannon* not only conceives the field of *Information Theory*, but also derives his famous channel capacity limit for *Additive White Gaussian Noise* (AWGN) channels. *Shannon* also shows that the channel capacity limit, which is a function of the transmission bandwidth and the *Signal-to-Noise Ratio* (SNR) of the AWGN channel being investigated, can be achieved by either increasing the number of transmission symbols in the signal space used during modulation, or by increasing the redundancy in the transmitted signals by incorporating channel coding into the communication system.

Unfortunately, *Shannon* could only postulate that good channel codes, which can achieve channel capacity, might exist. He was, however, unable to demonstrate how such codes were to be designed or selected. Hence, numerous communication engineers have devoted their research efforts to develop powerful channel codes during the span of the last 57 years. Their ongoing efforts have lead to four main categories within the channel coding field, namely block codes, convolutional codes, concatenated codes and coded modulation. Several important milestones that have been achieved during this time period include *Forney*'s 1966 proposal for classic concatenated codes [11], *Ungerboeck*'s 1982 introduction of *Trellis Coded Modulation* (TCM) [12] and the conception of *Turbo Code*s (TC) by *Thitimajshima et al.* in 1993 [13]. *Fig.* 1.1 shows a time line with these and other pivotal dates within the brief history of channel coding.

During the 1950's and 1960's channel coding subsystems were only incorporated into the communication systems designed by affluent government institutions, such as the *National Aeronautical and Space Association* (NASA). However, as the processing power and speed of digital circuitry, microprocessors and *Digital Signal Processor*s (DSP) increased, so also did the affordability of channel coding subsystems. For example, every *Compact Disc* (CD) *Read Only Memory* (ROM) drive currently manufactured employs non-binary *Reed-Solomon* (RS) block coding [14], which were thought to be extremely costly and complex to implement at the time of its inception in the early 1960's. Today, even the simplest digital communication systems contain some level of channel coding for error

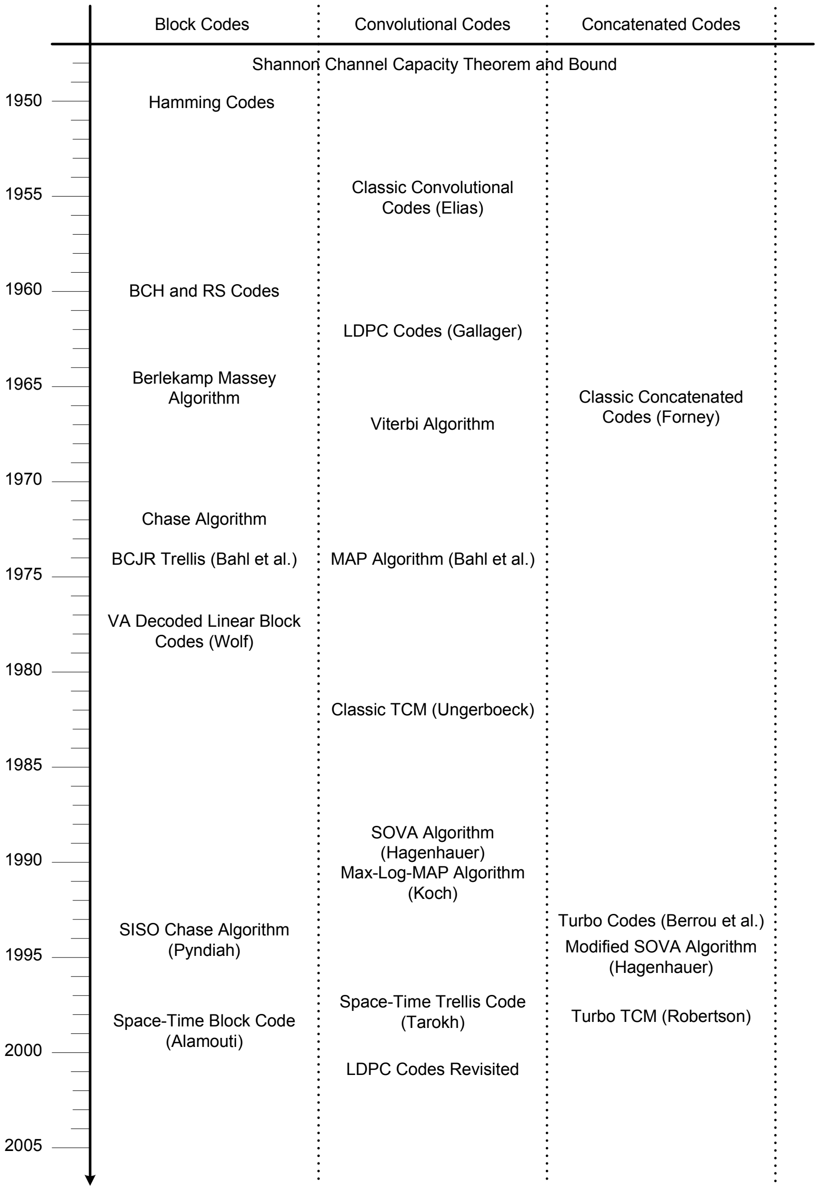

Figure 1.1: Time Line Showing Pivotal Events in Channel Coding History

detection and/or correction purposes. Current high-end communication systems, such as those used by *Jet Propulsion Labs*'s (JPL) deep space probes, make use of the latest generation iteratively decoded concatenated codes [15–33] and *Low Density Parity-Check Code*s (LDPC) [34] codes, which deliver *Bit-Error-Rate* (BER) performances close to the theoretical Shannon bound.

Recent years have seen several paradigm shifts with regards to the application of channel codes in communication systems. In the *Asynchronous Transfer Mode* (ATM) standard, for example, a linear block code is used to generate the *Header Error Control* (HEC) field of each 53-byte cell. The purpose of the HEC, however, is not just classic error detection and correction, but also cell delineation (i.e. frame synchronisation). Another paradigm shift of particular interest, is the move from classic *Forward Error Correction* (FEC) to *Error Control Coding* (ECC) approaches in modern channel coded communication systems: Classic FEC schemes attempt to correct all channel induced errors at the *Physical* (PHY) layer in the OSI model (i.e. layer 1) in a forward direction by performing receiver-end intelligent decoding of transmitted data streams, which have been padded with redundant information using channel coding in the transmitter. Conversely, an ECC scheme not only performs FEC using one of several channel codes available in its adaptive coding scheme, but also requests alternative encoding and/or retransmissions of previously transmitted streams of channel coded information, if it discovers that the initial decoding effort yielded an unacceptable BER at the receiver. This process is usually accomplished using higher layer protocols in the OSI stack, for example the *Transmission Control Protocol* (TCP) at the Transport layer in the OSI model (i.e. layer 4). ECC schemes, such as the *incremental redundancy* scheme implemented in *Enhanced Data Rates for GSM Evolution* (EDGE), is therefore capable of providing the necessary *Quality of Service* (QoS) levels desired by today's communication market.

The efficiency of ECC schemes is grounded in their ability to adapt the parameters of communication systems' channel coding subsystems in response to varying channel conditions. As such, a wide variety of channel codes, interleaver mappings and puncturing profiles constitute essential components of any powerful ECC scheme. However, an unfortunate disadvantage of adaptive coding schemes, which seems simple in principle, is that switching between several different channel encoder and decoder modules as the communication environment, changes can be a complex and expensive implementation exercise. Current hardware and software constraints on communication transceiver DSPs hamper the multiple implementation of complex encoder and decoder algorithms for different types of channel codes with varying degrees of complexity. Fortunately, this problem mainly befalls block codes, whereas multiple convolutional coding and TCM schemes can easily be supported by a single DSP, since the decoding of these codes rely on simple generic trellis-based algorithms. Each type of block code, however, typically has its own associated optimal *Maximum-Likelihood* (ML) decoding algorithm. In addition, these code-specific decoding algorithms are usually not capable of supporting soft decision decoding or making use of *Channel State Information* (CSI). In this study this issue is addressed by investigating the applicability of the *Viterbi Algorithm* (VA) as an efficient generic ML trellis decoding algorithm for both binary and non-binary linear block codes, operating on narrowband and wideband wireless communication systems in realistic mobile fading channel conditions.

1.1 PERTINENT RESEARCH TOPICS AND RELATED LITERATURE

1.1.1 MOBILE COMMUNICATION CHANNEL CHARACTERISTICS, MODELLING AND REPRODUCTION

Accurate characterisation and modelling of mobile communication channels play a key role in the design of modulation and channel coding techniques for wireless communication systems. Furthermore, being able to reproduce the statistical behaviour of such channels enables the communications engineer to rigourously test future wireless communication systems in controlled environments. For these reasons, countless hours of research and numerous publications have been devoted to both the mathematical characterisation [35–38] and the development of relevant simulation models [39–41] for real-life mobile communication channels.

When studying the performances of mobile communication systems, a usual starting point is an understanding of classic AWGN, since it is an unavoidable limiting factor in the performance and capabilities of any communication system. The primary source of a communication system's performance degradation due to this type of channel is receiver generated thermal noise, which is characterised as having a flat broadband spectrum and a zero-mean Gaussian amplitude *Probability Density Function* (PDF).

In realistic mobile communication environments, however, transmitted signals are not only influenced by AWGN, but also experience reflection, scattering and diffraction, due to surrounding objects in the propagation environment. Moreover, this results a received signal that is composed of a number of scattered wavefronts. The combining of these wavefronts in a receiver antenna produces constructive and destructive interference, resulting the well-known fading phenomenon, where the envelope and phase of the received signal vary stochastically [37, 38]. Additionally, relative motion between the transmitter and the receiver produces the undesirable Doppler effect, where a fixed or varied disturbance in carrier frequency can be experienced, respectively referred to as Doppler shift and Doppler spread [37,38].

During the simulation and performance evaluation of communication systems in controlled channel conditions, the ability to accurately describe and qualitatively classify the mobile fading environment is of cardinal importance. In general, the temporal and spectral disturbances experienced by a transmitted signal are the fundamental elements considered in the taxonomy of mobile fading channels:

1. **Temporal characteristics:** As the rate of relative motion between the transmitter and receiver structures of a mobile communication link increases, so also does the rate of signal fading, due to Doppler spreading. With respect to this fading rate, signal fading is categorised as either *slow fading* or *fast fading* [37,38,42]: When the Doppler spreading experienced by a transmitted signal is small compared to the actual information rate, the signal experiences slow fading. Moreover, in such a scenario a slow deep fade can potentially corrupt a large number of transmitted information symbols. Conversely, fast fading is earmarked by a high ratio of Doppler spreading to information rate, which produces shorter error burst at the receiver.

2. **Spectral characteristics:** Narrowband signals affected by realistic mobile fading channel conditions are distinguished, on a spectral level, by real-time uniform scaling of the *Power Spectral Density* (PSD) levels of the frequency components constituting the transmitted signal. This phenomenon, frequently observed when only a single propagation path exists, is known as *flat fading*. With wideband signals, however, it is not uncommon to observe several independently faded propagation paths from the transmitter to the receiver. Multipath propagation consequently produces non-uniform time-varying scaling of the PSD levels of the frequency components comprising the transmitted signal. In communications engineering nomenclature, this is known as *frequency selective fading* or *multipath fading* [37,38,42].

Through extensive simulations this study investigates the VA decoding of linear block codes on realistic communication links in lifelike mobile fading channel conditions. A classic narrowband *Quadrature Phase Shift Keying* (QPSK) communication system is used as simulation platform to evaluate such codes in pure AWGN channel conditions, typically encountered on stationary wireless links, such as *Wireless Local Loop*s (WLL). An identical QPSK communication system is used during the flat fading channel simulations in order to gauge the performance of VA decoded linear block codes on a typical narrowband mobile communication system. Slow and fast fading is considered in order to objectively analyse the influence of relative motion between the transmitter and receiver on the error correction capabilities of the VA decoded linear block codes. Since the needs for higher data rates and user capacity motivated the design of today's *Spread Spectrum* (SS)-based wideband 3G and *Beyond 3G* (B3G) systems, this study also considers the performance of the VA decoded linear block codes on a *Direct Sequence Spread Spectrum Multiple Access* (DS/SSMA) communication system in realistic multi-user multipath fading channel conditions.

1.1.2 SPREAD SPECTRUM WIDEBAND DIGITAL COMMUNICATION

While there does not appear to be a single *Multiple Access* (MA) technique in wireless communications that is superior, over the past two decades *Code Division Multiple Access* (CDMA) has been shown to be a viable (and in many applications even favorable) alternative to both *Frequency Division Multiple Access* (FDMA) and *Time Division Multiple Access* (TDMA) [43]. The greatest advantage that CDMA poses over other MA schemes, is its high frequency re-use capacity in cellular systems [43, 44]. Unlike narrowband FDMA-based and TDMA-based systems, such as GSM, there is little need to use different carrier frequencies in neighbouring cells. Thus, as the digital communications industry expands with the daily addition of thousands of new cellular subscribers, increasing the load on the available radio spectrum at an unparalleled rate, CDMA has become an indispensable MA technique for current 3G, B3G and future 4^{th} *Generation* (4G) cellular systems [45].

With superior anti-jamming and anti-interception characteristics, as well as unparalleled MA capabilities, SS modulation, the quintessential underlying principle behind CDMA, have long since been of great interest to the military community [43, 44]. However, due to its ability to mitigate or alleviate illustrious communication problems, such as spectral overcrowding, user privacy and security, multipath fading channel effects and indoor propagation issues [43, 44], SS has since been employed in several commercial wireless communication standards, such as *Qualcomm*'s 2^{nd} *Generation* (2G) IS-95 [46] system, as well as 3G *Universal Mobile Telephony System* (UMTS) and cdma2000 systems.

In essence, all variants of SS can be classified into two main categories [43, 44, 47]: *Direct Sequence Spread Spectrum* (DSSS) and *Frequency Hopping Spread Spectrum* (FHSS). Classically, in the latter category, the carrier frequency onto which information is modulated is determined by a random sequence, unique to each user in a multi-user system [43, 44, 47]. Using dynamic frequency allocation, FHSS systems can be designed to avoid interference encountered within the allocated operational bandwidth by simply eluding interference occupied frequency slots. It is also a well known fact [43] that FHSS systems mitigate multipath effects, provided that the hopping rate is in access of the inverse of the differential delay between multipath components. The relatively infant wideband *Orthogonal Frequency Division Multiplexing* (OFDM) SS technique [43], which is integrated into the IEEE 802.11 standard, can also be considered to be a FHSS derivative. Here, however, information is modulated onto several orthogonal carriers in order to obtain diversity gains. In DSSS systems information symbols are directly modulated by user-specific random spreading sequences (also sometimes called signature sequences) [43, 44, 47]. The spreaded information symbols of each user are then modulated onto a carrier in order to obtain a wideband *Radio Frequency* (RF) signal. Given that the cross-correlation levels of the spreading sequences employed in the DSSS system are small (ideally zero), negligible *Multi-User Interference* (MUI) is generated, thereby making it theoretically possible to use a single carrier frequency for all of the users in the CDMA system.

Undoubtedly the user capacity and bandwidth requirements of B3G and future 4G wireless communication systems will far exceed that currently delivered by 2G and 3G systems [45]. Thus, one can speculate that these systems will incorporate combinations of MA schemes in order to ensure acceptable QoS levels for all mobile subscribers. Hence, TDMA and FDMA will still be used in order to fulfill user load requirements in densely populated areas where CDMA alone will not suffice. *Spatial Division Multiple Access* (SDMA) is another advanced MA technique that will find its way from theory to practise in these systems. Furthermore, much of the current SS research is focused on *Multi-Carrier* (MC) DS/SSMA modulation variants [43, 44, 47]. These modulation schemes are essentially mixtures of OFDM and DS/SSMA, which does not only deliver substantial user capacities through CDMA, but also superior suppression of interference and multipath fading channel effects through frequency diversity. It is likely that one or more MC DS/SSMA modulation schemes will be incorporated into future 4G wireless PHY layer definitions [45].

The application of binary spreading sequences, such as *Gold* and *Kasami* sequences [48], in

DS/SSMA systems has been exhaustively investigated since the introduction of SS. However, due to the availability of potentially sizable families of spreading sequences that exhibit acceptable autocorrelation and cross-correlation properties when compared to binary sequences, interest has started to shift towards the use of non-binary and *Complex Spreading Sequence*s (CSS) [6, 48–51]. There are numerous advantages of using CSSs in future B3G and 4G DS/SSMA systems, including the possibility to generate CE and *Single Sideband* (SSB) [4, 7, 10] transmitter output signals [4]. In this study, VA decoded linear blocks are tested on a CSS-based DS/SSMA platform in multi-user multipath fading channel conditions in order to evaluate the viability of such codes in the adaptive coding schemes of future wideband SS-based communication systems.

1.1.3 TRELLIS DECODING OF LINEAR BLOCK CODES

In 1974 *Bahl et al.* [2] described a novel technique whereby minimal trellis structures (in this study referred to as *Bahl-Cocke-Jelinek-Raviv* (BCJR) trellis structures) can be constructed for linear block codes. Consequently, block code decoding was no longer limited just to classic suboptimal algebraic techniques. Soft decision decoding of block codes using the BCJR algorithm [2], or variants thereof, were also made possible through these trellis structures. Soon after the landmark publication by *Bahl et al.*, *Wolf* [3] proposed that, as a less complex alternative to the BCJR algorithm, the VA can be applied to block code trellises as an efficient soft decision ML decoder. Since *Wolf* did not validate or investigate this claim through simulation studies or hardware implementations, recent years have seen the publication of numerous papers [52–55] by *Staphorst et al.*, specifically devoted to the performance evaluation of VA decoded binary and non-binary linear block codes in varying mobile communication channel environments.

Although several algebraic soft decision block code decoding algorithms which employ CSI have been proposed, such as the popular algorithms by *Chase* [56] and *Moorthy et al.* [57], their performances have been showed [2, 58, 59] to be suboptimal. In contrast, both the BCJR *Maximum a-Posteriori Probability* (MAP) and Viterbi ML trellis decoding algorithms are optimal soft decision trellis decoders. A further advantage of the Viterbi and BCJR trellis decoding algorithms is their capacity to utilise CSI during their decoding efforts, resulting in improved BER performances when employed in fading channel conditions [60].

Due to the inherently intricate nature of the BCJR trellis structures of linear block codes, one serious impediment to the use of trellis decoders for linear block codes with practical block lengths and dimensions, is decoding complexity. Ergo, the current cost effectiveness of using trellis-based decoders in commercial applications, especially for powerful non-binary block codes, such as RS (see *Section* 3.2.2.3.3) and *Bose-Chaudhuri-Hocquenghem* (BCH) (see *Section* 3.2.2.3.2) block codes, are questionable. However, the number of efficient soft output algebraic decoding algorithms for block codes are minuscule when compared to soft output trellis decoding algorithms, traditionally developed for convolutional codes. Hence, trellis-based soft output decoding algorithms, such as the *Soft Output Viterbi Algorithm* (SOVA) [61], will become invaluable components in future iteratively decoded concatenated coding schemes employing linear block codes as *Constituent Code*s (CC). Furthermore, the promise of having a single trellis decoder module that can decode not only classic convolutional codes, but also linear block codes, is an attractive notion for the developers of digital communication systems.

1.2 MOTIVATION FOR THIS STUDY

In essence, researchers actively participating in the field of channel coding can be categorised into two main groups, namely the *Decibel Chasers* and the *Code Realisers*. The *Decibel Chasers* are researchers with the single-minded goal of creating new powerful channel coding schemes, capable of delivering BER performances that approach the Shannon bound [1,13,62]. Conversely, *Code Realisers* are more interested in translating the *Decibel Chasers*' theoretical and mathematical channel coding schemes into real-life hardware and/or software systems that can be integrated into commercial and military communication systems.

Since *Berrou*, *Glavieux* and *Thitimajshima*'s ground breaking paper [13] in 1993, which introduced the celebrated iteratively decoded TCs, the playing field for the *Decibel Chasers* have changed dramatically. Over the last decade, numerous new iteratively decoded *Parallel Concatenated Code*s (PCC) [15–26, 63–65], *Serial Concatenated Code*s (SCC) [27–31] and *Hybrid Concatenated Code*s (HCC) [30, 32, 33] have been proposed, capable of delivering BER performances within a fraction of a decibel from the Shannon bound [15, 21, 27, 32, 62–64, 66–69]. Gone are the days of code designers marvelling at substantial coding gains obtained from newly developed coding schemes. Presently, even a 0.01 dB improvement towards the theoretical Shannon bound, for example, is enough to create an uproar in the channel coding community.

Code Realisers have the difficult task of merging complex channel encoding and decoding algorithms with limited hardware and software platforms. This can be accomplished in two ways: Firstly, higher capacity and more scalable hardware and software platforms have to be developed, capable of supporting the requirements of new channel coding schemes. However, this is not the code designers responsibility, but rather that of DSP, *Field Programmable Gate Array* (FPGA) and *Application Specific Integrated Circuit* (ASIC) developers. Secondly, complex encoding and decoding algorithms, developed by the *Decibel Chasers*, have to be altered or condensed in order to conform with the available hardware and software platforms. Hence, the achievements of the *Code Realisers* always lag that of the *Decibel Chasers* and, to a fair extent, is paced at a rate of progression dictated by *Moore's Law* [70]. For example, in recent years JPL has devoted substantial funding and manpower on the research and development of iteratively decoded HCCs [30, 32, 33]. Since the encoding for HCCs is fairly straightforward, such encoder modules have already been implemented in the communication systems of NASA's newest generation deep space probes. However, the iterative decoding of HCCs is a mathematically complex and daunting exercise. As such, the *Code Realisers* at JPL are focused on the development of practical hardware and/or software iterative decoder modules for HCCs.

Optimal ML decoding of linear block codes through the application of the VA to their BCJR trellis structures [2], as proposed by *Wolf* in 1978 [3], is now a seasoned concept. Unfortunately, research in this field has remained fairly stagnant until the mid 1990's. This can be attributed mainly to the fact that the high complexities of BCJR trellises, even for rudimentary linear block codes, made hardware and/or software implementations of block code trellis decoders untenable. As new implementation platforms of higher speeds, capacities and scalability became available, renewed interest was sparked into the trellis decoding of linear block codes. Therefore, this study falls largely under the domain of the *Code Realisers*. From this perspective, the primary goals that motivated the research conducted during this study are the following:

1. Several advanced communication systems, such as EDGE, employ adaptive coding schemes, capable of dynamically switching between different block, convolutional and concatenated coding schemes in response to variations in the mobile channel environment and the users' QoS demands. Since the concept of *bandwidth-on-demand* is now well established and finding its way into the specifications of current communication systems, it is likely that adaptive coding will be an integral part of most future communication systems. In terms of implementation requirements, such adaptive coding schemes require extensive processing power and a multitude of decoding algorithms in

order to support an assortment of channel codes. Hence, having a single decoder algorithm, capable of decoding convolutional, block and concatenated codes, is an exiting proposition for *Code Realisers*. It is a well-known fact that the VA can be used as such a generic decoding algorithm. However, the application thereof to non-binary linear block codes, such as RS and BCH codes, have not been fully investigated in realistic mobile fading channels prior to this study. Also lacking prior attention, is the VA decoding of linear block codes in conjunction with code-augmentation techniques, such as interleaving and code puncturing.

2. Since the inception of the trellis decoding of linear block codes by *Bahl et al.* [2], *Code Realisers* have been faced with one unnerving implementation challenge: the storage and processing of the exceedingly complex BCJR trellis structures of linear block codes. This study attempts to address this problem by presenting and evaluating a promising BCJR trellis complexity reduction technique, applicable to both binary and non-binary linear block codes.

From a *Decibel Chaser*'s perspective, this study was motivated by the premise of obtaining improved BER performances for classic linear block codes in legacy digital communication systems by incorporating CSI into the VA's trellis decoding efforts. This is an attractive notion, especially since no additional hardware (except CSI estimators, which are usually already available) is required for potential coding gains in mobile fading channel conditions.

Secondary motivational factors that incited this study, rising from deficiencies identified within the general research field of channel coding, include the following:

1. The literature contains numerous simulation and performance evaluation studies of channel coding schemes in flat fading channel conditions. However, the greater majority of these studies are limited to pure Rayleigh flat fading channels. Furthermore, by typically assuming fading amplitudes which are *Independent Identically Distributed* (IID) for each code bit, channel code researchers neglect to investigate the effects of realistic Doppler effects. In *Section* 5.4.2 of this study presents a versatile flat fading performance evaluation platform, which addresses both of these deficiencies. Not only can this platform recreate realistic Rician fading amplitude distributions, but it also supports variable fading rates, ranging from slow to fast fading.

2. In general, most simulation studies presented in literature on the performance evaluation of channel coded DS/SSMA communication systems, operating in multi-user multipath fading channel conditions, also have much to be desired. Most of these studies assume non-realistic channel conditions and/or employ simplistic low-capacity spreading sequences, such as *Pseudo-Noise* (PN) codes. This study's wideband performance evaluation platform, presented in *Section* 5.4.3, recreates more realistic DS/SSMA communications in a multi-user multipath fading channel environment. The proposed simulation platform can be configured with realistic frequency selective fading channel conditions, unique to each user in the CDMA system. Furthermore, the DS/SSMA transmitter and RAKE receiver structures (presented in *Section* 5.3) support variable length binary or non-binary spreading sequence families. Hence, using this platform, channel coding schemes can be simulated on wideband wireless PHY layer configurations resembling the RF frontends of 3G, B3G and 4G systems.

3. Obtaining the simulated BER performance curve for an uncoded or coded communication system, without using theoretical upper or lower bounds, is an extremely lengthy and processor intensive task. The obstacle of excessive simulation execution time is addressed by this study on two fronts: Firstly, the AWGN, flat fading and multi-user multipath fading channel simulation platforms presented in this study were designed to operate purely in baseband, but recreate all channel phenomena experienced at any arbitrary carrier frequency. Secondly, the simulation software developed for this study distributes the computational load of the BER performance evaluation simulations over

the 16 processors constituting the *University of Pretoria*'s *I-percube High Performance Computing* (HPC) cluster, donated by *Intel*.

1.3 OBJECTIVES OF THIS STUDY

The primary goal of this study was the investigation and performance evaluation of VA decoded binary and non-binary linear block codes in AWGN, flat fading and multipath fading wireless channel environments. To that end, several secondary objectives had to be achieved. These are detailed below:

1. Thoroughly investigate the physical origins and accurately simulate the statistical behaviour of realistic mobile communication channel effects (see *Chapter* 2):
    (a) Scrutinise and reproduce classic AWGN channel effects.
    (b) Study the characterisation and mechanisms involved in flat fading. Topics of particular interest include Doppler spread effects and typical fading amplitude and phase distributions.
    (c) Research the elements partaking in frequency selective fading channels, including multipath propagation and time delay spread fading effects. Explore the characterisation and evaluation of these channels using concepts such as power delay profiles, time dispersion parameters and the concept of coherence bandwidth.
    (d) Design and implement a flexible flat fading channel simulator, capable of creating realistic Doppler spread effects, as well as Rayleigh and Rician fading amplitude distributions.
    (e) Develop and construct a versatile multipath fading channel simulator, composed of several flat fading channel simulators. This channel simulator must be capable of reproducing authentic multipath propagation and time delay spread fading effects.
    (f) Augment the proposed flat fading and multipath fading channel simulators in order to support full baseband simulation, thereby reducing processing power and execution time requirements.
2. Review the major building blocks that classic convolutional and linear block coding schemes are composed of (see *Chapter* 3):
    (a) Investigate the characteristics, encoder structures and trellis decoding of classic *Non-Systematic Convolutional* (NSC) and *Recursive Systematic Convolutional* (RSC) codes.
    (b) Mathematically describe the qualities, encoder structures and classic decoding techniques of the linear block codes of importance in this study, including binary Hamming, cyclic and BCH codes, as well as non-binary RS codes. A familiarisation with the Berlekamp-Massey syndrome decoding of non-binary RS codes forms an integral part of this investigation.
    (c) Inspect the concepts and mathematical portrayal of interleaving and de-interleaving, as well as puncturing and de-puncturing.
3. Explore the notion of linear block code trellis decoding via the application of the VA to BCJR trellises (see *Chapter* 4):
    (a) Study and implement the BCJR trellis construction method for linear block codes. Ascertain its usefulness with regards to non-binary linear blocks, such as RS codes.
    (b) Develop a simple trellis expurgation technique, applicable to both binary and non-binary linear block code BCJR trellis structures.
    (c) Define and determine the complexity of linear block code BCJR trellises.

   (d) Devise and demonstrate an effective, yet elementary trellis complexity reduction technique for binary and non-binary block code BCJR trellises.
   (e) Delve into the concepts and intricacies pertaining to the trellis decoding of binary and non-binary linear block codes via the application of the block-wise VA to BCJR trellises.
   (f) Research both hard and soft decision metric calculation approaches during the block-wise VA decoding of linear block codes. An investigation into the inclusion of fading amplitude CSI in the VA metric calculations is of foremost importance.

4. Establish flexible AWGN, flat fading and multipath fading performance evaluation platforms with authentic channel configurations (see *Chapter* 5):
   (a) Design and implement novel narrowband complex QPSK communication system simulation models, capable of functioning completely in baseband.
   (b) Extend the narrowband complex QPSK transmitter and receiver structures into flexible RAKE receiver-based wideband complex DS/SSMA QPSK communication system models, intended exclusively for baseband simulations. The proposed wideband complex DS/SSMA QPSK communication system must support complex spreading using unfiltered and pre-filtered CSSs for multi-user CDMA purposes.
   (c) Construct a flexible baseband AWGN channel performance evaluation platform using the novel narrowband complex QPSK transmitter and receiver structures.
   (d) Incorporate the proposed complex flat fading channel simulator into the AWGN performance evaluation platform, thereby creating an adjustable baseband flat fading channel simulation environment, supporting variable Doppler spreads and fading distributions.
   (e) Assemble a baseband multi-user multipath fading performance evaluation platform, comprising of the complex RAKE receiver-based DS/SSMA QPSK and multipath fading channel simulator system models. The proposed simulation platform must be capable of supporting flexible power delay profiles with uniquely definable Doppler spreads and fading distributions for each propagation path of each user in the CDMA environment.

5. Implement the performance evaluation platforms and conduct an extensive simulation study (see *Chapter* 6):
   (a) Using an *Object Orientated Programming* (OOP) approach in C++, implement all the simulation building blocks required to construct the proposed AWGN, flat fading and multi-user multipath fading channel performance evaluation platforms. These building blocks include: Gaussian and uniform noise generators, *Infinite Impulse Response* (IIR) and *Finite Impulse Response* (FIR) filters, convolutional coders and sliding window VA decoders, block coders and ML (classic and VA) decoders, interleavers and de-interleavers, puncturers and de-puncturers, complex flat and multipath fading channel simulators, narrowband complex QPSK transmitters and receivers, as well as wideband complex DS/SSMA QPSK transmitters and RAKE receivers.
   (b) Define the necessary simulation building block configurations, such as filter coefficients and impulse responses, block code generator matrices, convolutional code shift register configurations, trellis definitions, realistic flat and multipath fading channel configurations, pulse shape definitions, transmitter and receiver configurations, interleaver mappings, puncturing profiles, CSSs' real and imaginary parts, etc.
   (c) Verify the functionality of the newly constructed simulation building blocks. Special attention must be given to the proposed novel channel simulators, as well as the narrowband and wideband complex transmitter and receiver structures.

   (d) Using the simulation building blocks with their appropriate configurations, construct the AWGN, flat fading and multipath fading performance evaluation platforms in C++.
   (e) Implement the performance evaluation platforms on the *University of Pretoria*'s *I-percube* HPC cluster, donated by *Intel*.
   (f) Use the performance evaluation platforms to obtain simulated AWGN, flat fading and multiuser multipath fading BER performance results for narrowband and wideband systems employing classic convolutional codes, binary and non-binary linear block codes with VA decoding (using original and reduced complexity BCJR trellis structures), interleaved VA decoded convolutional and linear block codes, as well punctured VA decoded convolutional and linear block codes.

1.4 NOVEL CONTRIBUTIONS AND PUBLICATIONS EMANATING FROM THIS STUDY

1.4.1 NOVEL CONTRIBUTIONS

This study not only deliberated elements within the field of channel coding, but also investigated the characterisation and modelling of mobile communication channels, realistic narrowband and wideband communication systems, multi-user CDMA environments, and the creation of simulation platforms on multi-processor HPC clusters. As such, numerous contributions with varying degrees of importance and applicability were made in several research fields falling under the encompassing banner of digital communications. Excluding the introductory and final concluding chapters of this dissertation, each chapter ends with a short discussion on the innovative contributions it made. Below is a list with the most prolific contributions, compiled from these discussions:

1. Major contributions related to the research field of mobile communication channel modelling and reproduction:
   (a) A flexible complex flat fading channel simulator was developed, capable of producing Doppler spread effects and creating Rayleigh/Rician fading amplitude distributions (see *Section* 2.6.2.3). What sets this flat fading channel simulator apart from previous simulators, is the fact that it can realistically produce these channel effects in baseband, forfeiting the need for the communication system to operate at an actual RF.
   (b) Using multiple complex flat fading channel simulators, a generic complex multipath fading channel simulator structure was created (see *Section* 2.6.3.2). This frequency selective fading channel simulator can be configured to support any number of propagation paths (as defined by the required power delay profile), each with its own Doppler spread and fading distribution. As with the complex flat fading channel simulator, its novelty lays in the fact that it fully supports baseband simulations.
2. Major contributions related to the disciplines of information theory and channel coding:
   (a) A novel trellis expurgation (pruning) algorithm, applicable to both systematic binary and non-binary linear block codes' BCJR trellises, was derived (see *Section* 4.2.2).
   (b) Several existing BCJR trellis complexity calculation and reduction techniques, suitable only for binary linear block codes, were amalgamated and improved. The end result was a single BCJR trellis complexity calculation and reduction procedure, applicable to both binary and non-binary linear block codes (see *Section* 4.3).
   (c) *Wolf*'s original block-wise VA [3] for the ML decoding of linear block codes using their BCJR trellis structures, was upgraded to also incorporate fading amplitude CSI during its metric calculations (see *Section* 4.4).

3. Major contributions related to the modelling and simulation of communication systems:
    (a) Narrowband complex QPSK transmitter and receiver structures were fabricated (see *Section* 5.2). These building blocks' baseband functionality and the receiver's average fading amplitude CSI calculator (see *Section* 5.2.3) constitute novel contributions.
    (b) Wideband complex DS/SSMA QPSK transmitter and RAKE receiver structures, capable of employing unfiltered and filtered CSSs (see *Appendix D*), were created (see *Section* 5.3). The proposed DS/SSMA communication system employing these structures is unique for several reasons: Just as with the narrowband complex QPSK system, the wideband system operates entirely in baseband. It also employs its own novel average fading amplitude CSI calculator (see *Section* 5.3.3), based on the RAKE receiver's *Maximal Ratio Combining* (MRC) approach. Furthermore, this study also presents the first RAKE receiver-based implementation of DS/SSMA systems employing *Analytical Bandlimited Complex* (ABC) (see *Section* D.3.2.2) and *Double Sideband* (DSB) *Constant Envelope Linearly Interpolated Root-of-Unity* (CE-LI-RU) (see *Section* D.3.2.1) CSSs, whereas previously investigated systems [50, 51] only made use of simple correlator receivers.
    (c) A flexible AWGN performance evaluation platform, incorporating the novel narrowband complex QPSK transmitter and receiver structures, were developed (see *Section* 5.4.1). The evaluation of coded and uncoded narrowband QPSK systems in AWGN channel conditions was made possible by this platform.
    (d) Using the novel narrowband complex QPSK transmitter and receiver structures, as well as the unique complex flat fading channel simulator, a multifaceted flat fading performance evaluation platform was produced (see *Section* 5.4.2). This platform is capable of testing uncoded and coded narrowband QPSK communication systems in flat fading channel conditions with realistic Doppler spread effects and fading distributions.
    (e) A versatile multi-user multipath fading channel performance evaluation platform was produced (see *Section* 5.4.3) using the novel complex multipath fading channel simulator, as well as the wideband complex DS/SSMA QPSK transmitter and RAKE receiver simulation models. Using this platform, uncoded and coded wideband DS/SSMA QPSK communication systems can be evaluated in realistic frequency selective fading and/or multi-user CDMA environments.
    (f) The AWGN, flat fading and multi-user multipath fading simulation platforms created were fully implemented on the *University of Pretoria*'s *I-percube* HPC cluster, donated by *Intel*. All of *Chapter* 6's BER performance results were obtained using this HPC cluster.
4. Important and unique simulation results presented by this study, include:
    (a) various simulation results obtained using the novel complex flat fading and multipath fading channel simulators (see *Chapter* 6).
    (b) operational validation and simulated multi-user multipath fading BER performance results for uncoded and coded RAKE receiver-based wideband complex DS/SSMA QPSK communication systems employing CSSs (see *Chapter* 6).
    (c) simulation results investigating the influence of the CSS selection approach and sequence length on the BER performances of complex spreaded DS/SSMA systems, operating in multipath fading channel conditions.
    (d) simulated BER performance results for hard and soft decision VA decoded binary Hamming $(7, 4, 3)$ and non-binary RS $(7, 5, 3)$ linear block codes, obtained in AWGN, flat fading and multi-user multipath fading environments (see *Section* 6.5.3).

(e) simulated AWGN and flat fading BER performance results for hard and soft decision VA decoded binary cyclic $(5, 3, 2)$ linear block codes using original and reduced complexity BCJR trellis structures (see *Section* 6.5.4).

(f) simulated flat fading and multi-user multipath fading BER performance results for hard and soft decision VA decoded interleaved binary Hamming $(7, 4, 3)$ and non-binary RS $(7, 5, 3)$ linear block codes (see *Section* 6.5.5).

(g) simulated BER performance results for hard and soft decision VA decoded punctured binary BCH $(15, 7, 5)$ linear block codes in AWGN, flat fading and multi-user multipath fading channels (see *Section* 6.5.6.2).

(h) numerous simulation results investigating the BER performance improvements obtained by incorporating fading amplitude CSI into the soft decision VA decoding of linear block codes in fading environments (see *Chapter* 6).

1.4.2 PUBLICATIONS

During this study, the author researched and co-wrote three local conference papers, three international conference papers and a local journal article. Not only did these works lead to the development of a great number of the simulation building blocks crucial for this study, but also presented several relevant algorithms, concepts and simulation results. The following chronologically ordered list details the scope of these published papers, as well as their relevance to this study:

1. *”Trellis Decoding of Linear Block Codes”*, co-authored by *W.H. Büttner* and *Prof. L.P. Linde*, presented at IEEE COMSIG 1998 [52] at the *University of Cape Town*, *South Africa*, firstly describes the construction and expurgation of binary linear block code trellises, as suggested by *Bahl et al.* in [2]. In this paper the application of the VA as an efficient ML block code trellis decoder is investigated, followed by a complexity comparison between the VA trellis decoder and several classic algebraic decoding techniques, including classic ML and syndrome decoding. Simulated BER performance results for several VA trellis decoded binary linear block codes in AWGN channel conditions conclude the paper.

2. Obtaining the AWGN channel simulation results presented in the paper entitled *”Performance of a Synchronous Balanced QPSK CDMA System Using Complex Spreading Sequences in AWGN”* [50], co-authored by *M. Jamil* and *Prof. L.P. Linde*, required the development of flexible non-RAKE receiver-based DS/SSMA QPSK communication system building blocks. The transmitter and receiver building blocks of this paper, which was presented at IEEE AFRICON 1999 at the *Cape Town Technicon*, *South Africa*, are the forerunners of the DS/SSMA QPSK transmitter and RAKE receiver structures (see *Section* 5.3 of this dissertation) used in the simulation platform for the frequency selective fading channel simulations presented in *Chapter* 6. The paper also involved a thorough study of several classes of filtered and unfiltered CSSs. A lengthy *Gaussian Approximation* (GA)-based derivation of multi-user BER performance bounds for synchronous balanced QPSK CDMA communication systems employing such spreading sequences is also presented.

3. The development of a flexible multipath fading channel simulator (presented in *Section* 2.6 of this dissertation), used in the frequency selective fading channel simulations presented in *Chapter* 6 of this dissertation, was required to obtain the performance results given in the paper *”Performance Evaluation of a QPSK System Employing Complex Spreading Sequences in a Fading Environment”*, presented as a poster session at IEEE VTC-Fall 1999 in *Amsterdam*, *The Netherlands*. This paper [51], co-authored by *M. Jamil* and *Prof. L.P. Linde*, presents the AWGN and multipath fading channel BER performances of a synchronous non-RAKE receiver-based multi-user DS/SSMA system that employs CSSs with balanced QPSK modulation.

4. In the conference paper *”Performance Evaluation of Viterbi Decoded Reed-Solomon Block Codes in Additive White Gaussian Noise and Flat Fading Channel Conditions”* [55], written by *L. Staphorst* and *Prof. L.P. Linde*, presented at IEEE WCNC 2002 in *Orlando*, *Florida*, *USA*, simulated AWGN and flat fading channel BER performances for hard and soft decision VA trellis decoded non-binary RS $(7, 5, 3)$ codes, with code word symbols from Galois field $GF\left(2^3\right)$, are presented. The flat fading channel conditions considered included varying Rician factors (see *Section* 2.5.2.2 of this dissertation) and Doppler spreads (see *Section* 2.4.3.3 of this dissertation). In an attempt to improve on the classic hard and soft decision BER performance results, CSI (see *Section* 3.3.5 of this dissertation) is also included in the VA branch metric calculations (see *Section* 4.4.1 of this dissertation). The trellis expurgation technique presented in [52] for binary linear block codes is extended in this paper for non-binary linear block code trellises.

5. The simulated non-binary RS $(7, 5, 3)$ block code’s flat fading channel BER results given [55] are repeated in *”Performance Evaluation of Viterbi Decoded Binary and Non-binary Linear Block Codes in Flat Fading Channels”* [53], presented at IEEE AFRICON 2002, *George*, *South Africa*. This paper, authored by *L. Staphorst* and *Prof. L.P. Linde*, also presented novel flat fading channel simulated BER performance results for hard and soft decision VA decoded binary Hamming codes. Again the effects on the BER performances using CSI in the VA are considered.

6. In the IEEE CCECE 2003 poster session paper *”Performance Evaluation of a Joint Source/Channel Coding Scheme for DS/SSMA Systems Utilising Complex Spreading Sequences in Multipath Fading Channel Conditions”* [71], presented by *L. Staphorst*, *J. Schoeman* and *Prof. L.P. Linde* in *Montreal*, *Quebec*, *Canada*, the simple DS/SSMA QPSK communication system of [50] is upgraded to include a flexible RAKE receiver. This realistic multi-user wideband communication system was used in conjunction with the multipath fading channel simulator presented in [51] to determine the BER performance of a CSS-based CDMA system employing Huffman source coding and classic convolutional coding with joint VA decoding.

7. The journal article entitled *”On the Viterbi Decoding of Linear Block Codes”* [54], authored by *L. Staphorst* and *Prof. L.P. Linde*, was published in the Transactions of the SAIEE in December 2003. This article restates all algorithms, as well as AWGN and flat fading channel simulation results presented in [52], [55] and [53]. Furthermore, the trellis complexity calculation and reduction algorithms presented in *Section* 4.3.1 and *Section* 4.3.2 of this dissertation, respectively, are explained in this paper. Simulated AWGN and flat fading channel BER performance results for a cyclic $(5, 3, 2)$ linear block code with VA decoding using original and reduced trellis structures are also presented. It is important to mention that this paper was reviewed and accepted without any changes by *Prof. J.K. Wolf*, who is seen as the father of the Viterbi decoding technique for linear block codes.

8. The following two paper series, authored by *L. Staphorst* and *Prof. L.P. Linde*, were published in the proceedings of the AFRICON 2004 conference and presented in September 2004 at *Gaborone, Botswana*:

   (a) *”Evaluating Viterbi Decoded Reed-Solomon Block Codes on a Complex Spreaded DS/SSMA CDMA System: Part I - Background and Communication System Models”* [72].

   (b) *”Evaluating Viterbi Decoded Reed-Solomon Block Codes on a Complex Spreaded DS/SSMA CDMA System: Part II - Channel Model, Evaluation Platform and Results”* [73].

   These two papers firstly present the complex multipath fading channel and RAKE receiver-based DS/SSMA QPSK communication system simulation models described in *Chapter* 5. This is followed by an overview of the simulation platform and configuration parameters used to obtain the wideband simulation results presented in *Chapter* 6. Lastly, simulated BER performance results are presented for RS $(7,5,3)$ coded RAKE receiver-based DS/SSMA QPSK communication systems, employing the different CSS families presented in *Appendix D*, under realistic multi-user multipath channel fading effects.

1.5 ORGANISATION OF THE DISSERTATION

This dissertation consists of seven chapters. The contents of the chapters are as follows: *Chapter* 1 sets out by giving short introductions and historical overviews into wireless communication over mobile communication channels, the conception and evolution of channel coding, as well as the trellis decoding of linear block codes. This is then followed by the objectives that had to be met by this study, which collectively addressed the main problem statement of the performance evaluation of VA decoded binary and non-binary linear block codes, operating in mobile communication channel conditions. Next, the main contributions made by this study are summarised. Lastly, *Chapter* 1 lists a number of published conference and journal articles originating from the work presented in this dissertation.

The analyses and modelling of mobile fading channels are the focus areas of *Chapter* 2. Firstly, the mathematical description and statistical characteristics of AWGN, flat fading and frequency selective fading channels are considered. This is then followed by the development of the novel complex flat and frequency selective fading channel simulator models employed during the performance evaluation of the VA decoded linear block codes considered in this study.

Chapter 3 gives an overview of the main building blocks used in classic block and convolutional coding schemes. Encoder building blocks considered include: Convolutional coders, block coders, interleavers and code puncturers. Block and convolutional decoding algorithms, de-interleavers, code de-puncturers and CSI estimators are discussed under the topic of decoder building blocks.

The VA decoding of linear block codes is described in *Chapter* 4. This discussion includes the construction and reduction of linear block code trellis structures, as well as a thorough explanation of the block-wise VA applied to these trellis structures. Special attention is given to the inclusion of CSI in the VA's decoding efforts. Short theoretical derivations of the BER performances of VA decoded linear block codes in AWGN and flat fading channel conditions conclude this chapter.

The narrowband complex QPSK and wideband RAKE receiver-based DS/SSMA QPSK communication systems, employed in the simulations performed for this study, are described in *Chapter* 5. Following the descriptions and analyses of the proposed narrowband and wideband communication systems, is a discussion on the simulation platforms used in the AWGN and flat fading channel performance evaluation tests, built around the narrowband complex QPSK communication system. Finally, the simulation platform used for the multi-user multipath fading channel performance evaluation tests, assembled using the novel wideband complex RAKE receiver-based DS/SSMA QPSK communication system, is described.

Chapter 6 presents the simulation results obtained during this study. Firstly, simulation results that validate the operation of the novel complex flat fading and multipath fading channel simulator models are given. Next, simulation results to validate the functioning of the narrowband complex QPSK and wideband RAKE receiver-based complex DS/SSMA QPSK communication systems are presented. Lastly, a large number of simulated BER performance results are presented for the coding schemes considered in this study, evaluated on the narrowband and wideband communication platforms under AWGN, flat fading and frequency selective fading channel conditions. These coding schemes include various VA decoded binary convolutional codes, as well as VA decoded binary and non-binary linear block codes. Employing original and reduced complexity BCJR trellis structures during the VA decoding of linear block codes are also scrutinised here, as well as the effects of performing puncturing and interleaving in conjunction with channel coding.

In *Chapter* 7 conclusions are drawn from the results obtained. During this study a number of areas have been identified for possible future research. These future research areas are also discussed in *Chapter* 7.

Five appendices, covering topics of importance to the understanding of the subject matter investigated in this study, follow the seven chapters outlined above: *Appendix A* lists the encoder parameters of different code rate optimal RSC codes, constructed by *Benedetto*, *Garello* and *Montorsi*. A simple example of the use of these parameters are also given. A conceptual description of the *Berlekamp-Massey* decoding algorithm [74, 75], frequently employed in the syndrome decoding of classic BCH and RS block codes, is presented in *Appendix B*. Although the algorithm is not described in detail, the major functions that it performs in its syndrome decoding efforts are described in this appendix. *Appendix C* considers a number of popular block interleaver structures, frequently encountered in iteratively and non-iteratively decoded concatenated coding schemes. These include deterministic and random interleaver structures. *Appendix D* summarises some of the important performances measures utilised in the analysis of CSSs. It also gives concise overviews of the filtered and unfiltered CSS families considered in this study. *Appendix E* supplies the reader with an extensive index of the simulation software developed for this study, including the Matlab functions and scripts, as well as C++ classes and compiled executables.