CHAPTER SEVEN

CONCLUSIONS AND FUTURE RESEARCH

7.1 CHAPTER OVERVIEW

THE most significant conclusions forthcoming from the body of work presented in this study are detailed in the first section of this final chapter. This is then followed by a number of possible related research areas, identified during the run of the study.

7.2 CONCLUSIONS

This study thoroughly examined the viability of the VA as an efficient ML trellis decoder for linear block codes in future wireless communication systems. Several VA decoded binary and non-binary linear block codes were extensively evaluated on narrowband QPSK and wideband DS/SSMA QPSK communication systems, operating in realistic mobile communication channel conditions, ranging from pure AWGN to multi-user multipath fading. Not only was the influence of different mobile channel effects on the BER performances of VA decoded binary and non-binary linear block codes considered, but also that of interleaving, puncturing, MUI and improved VA metric calculations that make use of fading amplitude CSI. From the body of work presented in this study, a large number of conclusions can be drawn. The most significant findings are listed below:

1. Conclusions pertaining to the operation and statistical behaviour of the novel complex flat fading and multipath fading channel simulator structures, presented in *Section* 2.6.2.3 and *Section* 2.6.3.2, respectively:
    (a) From *Section* 6.2.1's measured Doppler spectra, as well as fading amplitude and phase PDF's, it is apparent that the novel *Clarke*-based complex flat fading channel simulator, presented in *Section* 2.6.2.3, is capable of recreating flat fading channel conditions with realistic Doppler spreading and fading distribution characteristics. Most importantly, the proposed flat fading channel simulator structure is capable of doing so completely in baseband, eliminating the need for undesirable carrier frequencies during simulation studies.
    (b) Using *Section* 2.6.3.3's proposed exponential decay power delay profile creation method, the novel complex multipath fading channel simulator, presented in *Section* 2.6.3.2, can be configured to recreate realistic outdoor frequency selective channel conditions, ideal for the testing of wideband communication systems. The results shown in *Fig.* 6.2.2.1 not only prove that the proposed complex multipath fading channel simulator is capable of creating different fading distributions on each of the propagation paths, but also distinct Doppler spreads.

   (c) *Eq.* (2.56) and *Eq.* (2.57) enables the communication engineer to extract perfect fading amplitude and phase CSI, respectively, for each flat fading propagation path in the complex multipath fading channel simulator of *Fig.* 2.8. The extracted CSI can then be processed in the receiver of the communication system under investigation for the purposes of carrier tracking, code locking, improved decoder metric calculations, etc.

2. Conclusions relating to the theoretical analysis and functioning of the novel narrowband complex QPSK and wideband RAKE receiver-based complex DS/SSMA QPSK communication system models, introduced in *Section* 5.2 and *Section* 5.3, respectively:

   (a) The narrowband complex QPSK transmitter and receiver simulation models, presented in *Section* 5.2, can be used to create baseband AWGN and flat fading channel performance evaluation platforms for narrowband communication systems that support realistic carrier tracking, transmit and receive filtering, pulse shaping and matched filtering. In the complex QPSK receiver, *Eq.* (5.2.3) can be used to obtain accurate average fading amplitude estimates, which is required by most CSI-enabled channel decoder structures.

   (b) *Section* 5.3 introduced novel wideband complex DS/SSMA QPSK transmitter and RAKE receiver simulation models, capable of supporting the unfiltered and filtered CSS families presented in *Appendix D*. These simulation models can be used to construct baseband performance evaluation platforms that represent realistic CDMA systems in frequency selective fading environments. Furthermore, not only can the communications engineer use the baseband equivalent models to investigate the performance of channel coding schemes, but also carrier tracking loops, power control schemes, code locked loops, pulse shaping filters, RAKE combining techniques, the MUI characteristics of different CSS families, etc. Furthermore, average fading amplitude calculation through *Eq.* (5.3.3) can be used to determine CSI for SISO-type channel decoder structures.

3. Conclusions regarding the configurability, general operation and relevance of the flexible AWGN (see *Section* 5.4.1), flat fading (see *Section* 5.4.2) and multi-user multipath fading channel (see *Section* 5.4.3) performance evaluation platforms constructed for this study:

   (a) The performance evaluation platform shown in *Fig.* 5.5 can be used to investigate the performance of different channel coding schemes when implemented in a typical narrowband digital communication system, operating in realistic AWGN channel conditions. Thus, uncoded and coded narrowband QPSK communication systems, operating in channel conditions without any fading effects (i.e. when there is no relative movement between the transmitter and receiver structures), can be recreated using this simulation platform.

   (b) Coded and uncoded narrowband QPSK communication systems, operating in a wide variety of flat fading channel conditions, can be investigated using the performance evaluation platform of *Fig.* 5.8 in *Section* 5.4.2. This flat fading channel performance evaluation platform can not only be configured to recreate Rayleigh or Rician fading distribution, but also realistic Doppler spreads. Hence, the performance of different channel coding schemes, implemented in narrowband QPSK communication systems, can be experimentally determined for slow or fast flat fading channel conditions with varying degrees of LOS signal strength.

   (c) The influence of realistic multipath fading channel effects on uncoded and coded wideband DS/SSMA systems can be experimentally investigated by means of the multi-user performance platform, shown in *Fig.* 5.9. Each CDMA user active in the simulation platform, can be assigned its own unique power delay profile in order to recreate realistic movement of mobile users in a cellular environment. Furthermore, the influence of MUI, the near-far effect and the accuracy of the RAKE receiver's MRC efforts on the user capacity and BER performance of the DS/SSMA system, can also be explored using this platform.

   (d) The AWGN, flat fading and multi-user multipath performance evaluation platforms, detailed in *Chapter* 5, were successfully implemented in C++ on the *University of Pretoria*'s *I-percube* HPC cluster, donated by *Intel*. Using this HPC cluster, numerous simulated BER performance results were efficiently and swiftly obtained for a wide variety of uncoded and coded narrowband and wideband communication systems in varying mobile channel conditions (see *Chapter* 6).

4. Conclusions from the extensive investigation into the construction, complexity calculation and complexity reduction of linear block code BCJR trellises, as well as the application of the block-wise VA to these trellis structures for optimal ML decoding (see *Chapter* 4):

   (a) Unlike convolutional codes, linear block codes are not state machines. Hence, the orthodox approach whereby a convolutional code's trellis diagram is constructed by creating a time-indexed version of its state diagram, is not applicable to linear block codes. However, following the BCJR syndrome-based trellis construction procedure, described in *Section* 4.2, an irregular trellis-like structure, containing paths representing only valid code words, can be created for any binary or non-binary linear block code.

   (b) BCJR trellis structures of linear block codes always start and end in state 0. Hence, in contrast to convolutional codes, no termination or tail biting overhead bits are required by a linear block coder in order to supply the associated trellis decoder with known starting and ending states. Thus, the trellis decoding of a linear block code is by default a block-wise operation, eliminating the need for sliding window decoders, or intricate interleaver designs when such codes are used as CCs in iteratively decoded PCCs.

   (c) The complexity (i.e. number of active nodes and branches) of a linear block code's BCJR trellis can be obtained from its state space profile, as described in *Section* 4.3.1. In general, for the (n, k, d_{min}) linear block code C, having code and message word symbols from $GF\left(2^{\xi}\right)$, the number of active nodes $AN(C)$ is upper bounded by the dimensions of its BCJR trellis. Since a BCJR trellis consist of $n+1$ sets of nodes, each set of nodes consisting of $2^{\xi(n-k)}$ unique states, it follows that $AN(C) < 2^{\xi(n-k)}(n+1)$. Furthermore, with $AN(C)$ known, the number of branches in an expurgated trellis is upper bounded by $NB(C) \leq 2^{\xi}(AN(C)-1)$ (see *Section* 4.3.1).

   (d) Unfortunately, the BCJR trellis structures required for the effective trellis decoding of powerful linear block codes (i.e. low rate codes with high $(n-k)$), are exceeding large. This is especially true for non-binary codes, such as RS block codes, operating in $GF\left(2^{\xi}\right)$ with $\xi > 1$. By comparing the complexity of the BCJR trellis of a binary (n, k, d_{min}) linear block code with that of a non-binary (n, k, d_{min}) linear block code, operating in $GF\left(2^{\xi}\right)$, it is apparent that the number of branches emanating from an active node in an BCJR trellis does not only increase exponentially with ξ, but so also does the number of unique states.

   (e) The trellis reduction method presented in *Section* 4.3.2 was shown to be successful in obtaining equivalent linear block code generator matrices that exhibit lower complexity BCJR trellis structures. Unfortunately, the proposed trellis complexity reduction scheme requires an exhaustive search through all equivalent generator matrices in order to find those demonstrating the lowest state space complexities. This becomes an arduous task for linear block codes with large dimensions. Luckily, the search process only has to be conducted once during code design, prior to the hardware and/or software implementation of an appropriate trellis decoder.

   (f) In contrast to classic sub-optimal soft input linear block code decoding algorithms, such as the algorithms proposed by *Chase* [56] and *Moorthy et al.* [57], the block-wise VA algorithm can efficiently accomplish optimal soft input ML decoding for any type of binary or non-binary linear block code.

   (g) It is safe to assume that most future mobile communication systems will support adaptive channel coding schemes, capable of dynamically adjusting the level of error protection provided as a function of the channel characteristics and the end-users' required QoS profiles. The concept of *incremental redundancy*, introduced in EDGE, is an excellent example of current commercial systems that already incorporate adaptive channel coding. Furthermore, with the processing power of DSPs and ASICs rapidly increasing, the incorporation of iteratively decoded concatenated codes (such as TCs) in the suite of codes supported by future commercial communication systems' adaptive channel coding schemes, is becoming a reality. Since most SISO-based iterative decoding algorithms require accurate CSI parameters, CSI estimators (see *Section* 3.3.5) will become indispensable peripheral hardware/software in future adaptive channel coding subsystems. This study showed that, using the fading amplitude CSI obtained by such estimators, fading channel BER performances of classic linear block codes, possibly incorporated in the suites of supported channel codes of future adaptive channel coding schemes, can be improved by as much as 0.5 dB.

5. General conclusions from the simulated BER performance results for uncoded and coded narrowband complex QPSK communication systems, operating in AWGN channel conditions (see *Section* 6.5):

   (a) The AWGN channel BER performance results, presented in *Chapter* 6, is evidence that the performance evaluation platform presented in *Section* 5.4.1 is capable of precisely reproducing the operations of uncoded and coded narrowband QPSK communication systems in fade-free, pure AWGN channel conditions.

   (b) Inspection of the simulated AWGN BER performances obtained for the binary and non-binary linear block codes investigated in this study, establishes that the VA decoding approach produces BER performance results equivalent to that obtained through classic optimal ML exhaustive code book searches. This is not only true for hard and soft decision trellis decoding using the original BCJR trellis structures, but also when reduced complexity BCJR trellis structures are used.

   (c) Typical asymptotic gains, ranging from 1.9 dB (VA decoded binary Hamming $(7,4,3)$ code) to 3 dB (VA decoded punctured binary BCH $(15,7,5)$ code), were observed for hard decision over soft decision VA decoding. Thus, the soft input VA decoding of linear block codes produces better AWGN BER performances than those obtained through classic hard decision decoding algorithms, such as the Berlekamp-Massey algorithm for non-binary RS block codes.

6. General conclusions from the simulated BER performance results for uncoded and coded narrowband complex QPSK communication systems, operating in flat fading channel conditions (see *Section* 6.5):

   (a) The ability of the flat fading channel performance evaluation platform, presented in *Section* 5.4.2, to accurately reproduce the operation of uncoded and coded narrowband QPSK communication systems in flat fading channel conditions with varying Rician factors and Doppler spreads, is reflected by the myriad of flat fading channel BER performance results presented in *Chapter* 6.

   (b) The PDF of the fading amplitude created by a flat fading channel ranges from pure Rayleigh to pure Gaussian as the ratio of LOS to NLOS signal components vary from $-\infty$ dB to ∞ dB. Furthermore, the convolutional and linear block codes investigated in this study are best suited for mobile communication channels generating Gaussian-like signal amplitude PDFs. Hence, the general tendency of coded narrowband complex QPSK communication systems to exhibit increased BER performances in flat fading channel conditions as the Rician factor increases, can be observed from the simulated BER performance results of *Chapter* 6.

(c) As the ratio of maximum Doppler spread to transmitted symbol rate of a narrowband digital communication system, which utilises a flat fading channel as transmission medium, increases, one intuitively expects the number of symbols lost due to deep fades to decrease. For example, for the $B_D = 100$ Hz fast flat fading channel scenario considered in this study, this ratio calculates to 10% for the selected transmitted symbol rate of 1000 symbols/s. Thus, using a simple rule-of-thumb calculation, it is safe to assume that on average 10 coded symbols will be lost per deep fade in such flat fading channel conditions. Similarly, for the $B_D = 33$ Hz slow flat fading scenario investigated in this study, the ratio of maximum Doppler spread to transmitted symbol rate calculates to 3.3%, which in turn translates to an average loss of 30 bits per deep fade. Hence, assuming a fixed transmitted symbol rate, the average size of an error burst, induced by flat fading channel conditions, increases as the maximum Doppler spread decreases. Moreover, all channel coding schemes have limited burst error correction capabilities, depending on the complexity of the Galois field used for message and code word symbol representation. Hence, the decrease in BER performance as the maximum Doppler spread decreases relatively to the fixed transmitted symbol rate of 1000 symbols/s, observed for all of *Chapter* 6's coded narrowband complex QPSK systems in flat fading channel conditions, was to be expected.

(d) Closer inspection of the simulated BER performance results of *Section* 6.5.1.2 shows that an uncoded narrowband complex QPSK communication system, operating in a Rayleigh flat fading channel with a maximum Doppler spread of $B_D = 33$ Hz, performs close to the theoretical bound of *Eq.* (5.24), whereas the results obtained for $B_D = 100$ Hz deviates significantly from the theoretical curve at high E_b/N_0 levels. This is easily explained: The theoretical curve of *Eq.* (5.24) was derived under the assumptions of slow IID Rayleigh flat fading. Although these assumptions are idealistic, it does resemble the characteristics of realistic flat fading channels with low maximum Doppler spreads, i.e. slow flat fading channels where the fading amplitude does not vary significantly during a single transmitter symbol period.

(e) *Chapter* 6's simulated BER performance results for VA decoded binary convolutional and linear block codes, implemented on narrowband QPSK communication systems in flat fading channel conditions, demonstrate that maximum asymptotic gains in the region of 2 dB can be obtained using hard decision over soft decision (without fading amplitude CSI) ML decoding. In the case of the non-binary RS $(7, 5, 3)$, however, this gain was close to 3 dB for fast fading and high LOS channel conditions. Thus, the standard assumption that hard decision ML decoding usually lags soft decision ML decoding by 2 dB does not hold for all types of channel codes and for all flat fading channel conditions.

(f) The inclusion of perfect fading amplitude CSI in the metric calculations of the VA during soft decision decoding proved to fortify the BER performances of both binary and non-binary linear block codes and convolutional codes in flat fading channel conditions. This was most notable for the non-binary RS $(7, 5, 3)$ linear block code, where a gain of 0.4 dB was obtained by soft decision VA decoding with perfect fading amplitude CSI for a maximum Doppler spread of $B_D = 100$ Hz and Rician factor of $K_i = 9$ dB. In general, one can conclude that the improvements delivered by incorporating fading amplitude CSI during the soft decision VA decoding of convolutional and linear block codes decrease as the maximum Doppler spread (i.e. fading rate) and Rician factor (i.e. LOS signal strength) of the flat fading channel decrease.

7. General conclusions from the simulated BER performance results for uncoded and coded wide-

band complex DS/SSMA QPSK communication systems, operating in multi-user multipath fading channel conditions (see *Section* 6.5):

(a) From *Chapter* 6's host of multi-user multipath fading channel BER performance results, it can be concluded that the performance evaluation platform presented in *Section* 5.4.3 enables the communications engineer to investigate not only different coding schemes for wideband DS/SSMA systems in frequency selective fading channel conditions, but also the MUI resilience of different spreading sequence families and the effectiveness of RAKE combining techniques. As such, it is an essential simulation tool for research into future B3G and 4G PHY layer architectures.

(b) For 1-user and 5-user scenarios, CSS-based DS/SSMA communication systems employing RAKE reception and any of the four CSS families described in *Appendix D*, perform superior to non-RAKE receiver-based systems. In fact, for the single user case, the MRC diversity action of the RAKE receiver in multipath fading proved to be so successful that it even outperforms a narrowband complex QPSK system operating in a flat fading channel with $K_i = 9$ dB and $B_D = 100$ Hz. Thus, RAKE reception can be used successfully to obtain diversity gains in DS/SSMA communication systems employing filtered or unfiltered CSSs.

(c) The use of RAKE reception in a 10-user ABC sequence-based DS/SSMA system delivered weaker BER performances than a non-RAKE receiver-based system. For the DSB CE-LI-RU filtered GCL, QPH and ZC CSS families, however, RAKE reception delivered superior performances at even such high user loads. Therefore, one can conclude that the poor periodic auto-correlation and cross-correlation properties of ABC sequences [48] generate excessive self-noise in a standard RAKE receiver structure, which has been optimally configured to combine the different paths in the power delay profile of the multipath fading channel.

(d) As was to be expected, the MUI generated at high user loads influence the BER performance of the CSS-based wideband complex DS/SSMA communication systems negatively, resulting in persistent error floors at high E_b/N_0. It is interesting to note, however, that the degradation in performance due to MUI is more severe for the DS/SSMA systems employing filtered CSSs. Thus, one can conclude that the *Root-of-Unity* (RU) interpolation filtering techniques [7, 8] used to construct ABC and DSB CE-LI-RU filtered GCL CSSs, degrade the periodic cross-correlation characteristics of the parent ZC CSSs, resulting in higher MUI levels.

8. Conclusions from the simulated BER performance results for binary rate $R_c = 1/2$ NSC and rate $R_c = 2/3$ RSC codes, operating in varying mobile communication channel conditions (see *Section* 6.5.2):

(a) In AWGN channel conditions the binary rate $R_c = 1/2$ NSC and rate $R_c = 2/3$ RSC codes considered in this study performs comparably. However, due to its lower d_{free}, the NSC code lags slightly at low E_b/N_0. Thus, the classic belief that, in non-concatenated coding schemes the use of NSC codes is preferable over RSC codes due to their superior performance at low E_b/N_0 in AWGN conditions, did not hold in this study.

(b) From the flat and multipath fading simulation results it is apparent that the NSC code is better suited at combatting bursty errors. The RSC code's poor performance can be attributed to its recursive nature, a characteristic which makes RSC codes prone to error propagation when presented with correlated error bursts.

(c) As demonstrated by the multi-user multipath fading simulated BER performance results, the binary rate $R_c = 1/2$ NSC and rate $R_c = 2/3$ RSC codes proved to be the most effective in suppressing MUI for all of the codes considered in this study. Thus, from this observation one can conclude that even simple convolutional codes are more effective at suppressing the errors caused by the MUI, present in DS/SSMA systems at high user loads, than powerful linear block codes.

   (d) CSI-enhanced soft decision sliding window VA decoding of the NSC code in fading channel conditions showed BER performance improvements, ranging between 0.15 dB and 0.25 dB, over standard soft decision sliding window VA decoding. In the case of the RSC code, the observed improvements ranged between 0.1 dB and 0.2 dB. One can therefore conclude that the inclusion of fading amplitude CSI in the soft decision VA decoding of convolutional codes is not as effective as with the soft decision VA decoding of linear block codes.

9. Conclusions from the simulated BER performance results for VA decoded binary Hamming $(7,4,3)$ linear block codes, operating in varying mobile communication channel conditions (see *Section* 6.5.3.1):

   (a) From the AWGN, flat fading and multi-user multipath fading channel BER performance results presented in *Section* 6.5.3.1, one can conclude that the VA decoding of binary linear block codes, using BCJR trellis structures, deliver hard and soft decision BER performances matching those of classic ML decoding, based on brute force code book searches.

   (b) Flat and multipath fading channel BER performance results demonstrate that the inclusion of perfect fading amplitude CSI in the metric calculations, during the VA decoding of the binary Hamming $(7,4,3)$ linear block code, can improve soft decision ML decoding's BER performance by 0.2 dB to 0.4 dB, depending on the temporal and spectral characteristics of the fading channel. It is important to note the use of fading amplitude CSI is less effective for multipath fading channel conditions.

   (c) Overall, the binary Hamming $(7,4,3)$ linear block code considered in this study performed poorly, due to its low d_{min}. This is especially true for fading channel conditions, since it is not capable of correcting bursty errors.

10. Conclusions from the simulated BER performance results for VA decoded non-binary RS $(7,5,3)$ linear block codes, operating in varying mobile communication channel conditions (see *Section* 6.5.3.2):

   (a) Hard decision VA decoding of the non-binary RS $(7,5,3)$ linear block code, operating in AWGN, flat fading and multi-user multipath fading channel conditions, delivers BER performances equivalent to that obtained using the classic Berlekamp Massey syndrome decoding approach. One can therefore conclude that the VA is capable of performing optimal ML decoding of non-binary linear block codes.

   (b) The simulated BER performance results show that optimal soft decision ML decoding of non-binary codes, such as RS codes, is possible through the application of the VA to these codes' BCJR trellis structures. Asymptotic gains as high as 3 dB above hard decision decoding was achieved for the non-binary RS $(7,5,3)$ code, depending on the channel characteristics.

   (c) Simulated BER performance results for flat and multipath fading channels show that, as with the binary Hamming $(7,4,3)$ linear block code, the use of fading amplitude CSI during soft decision VA decoding of the non-binary RS $(7,5,3)$ code improves on standard soft decision decoding by as much as 0.4 dB. The factors that influence the gains achievable through the inclusion of fading amplitude CSI, is discussed in detail later in this subsection.

   (d) The non-binary RS $(7,5,3)$ linear block code proved to be more effective than the binary Hamming $(7,4,3)$ code at combatting the bursty errors produced by fading channel conditions. This was to be expected, since RS codes are burst error correcting codes.

   (e) Unfortunately, non-binary linear block codes, such as RS codes, possess exceedingly complex BCJR trellis structures. For example, the simple RS $(7, 5, 3)$ code considered in this study has a BCJR trellis consisting of 8 layers of nodes, each layer containing 64 nodes with 8 branches emanating from each active node. Thus, one can argue that the gains achievable over classic non-binary linear block code decoding algorithms, such as the Berlekamp Massey algorithm, through soft decision VA decoding and the application of fading amplitude CSI, do not justify the increase in decoder complexity and implementation hardware/software requirements.

11. Conclusions from the simulated BER performance results obtained by using reduced complexity BCJR trellis structures during the VA decoding of binary cyclic $(5, 3, 2)$ linear block codes, operating in varying mobile communication channel conditions (see *Section* 6.5.4):

    (a) In AWGN channel conditions, the VA decoding of the binary cyclic $(5, 3, 2)$ linear block code, using the standard and reduced complexity BCJR trellis structures, delivered equivalent BER performances. Therefore, it is safe to assume that the trellis reduction algorithm presented in *Section* 4.3.2 is successful in obtaining less complex and easier implementable equivalent BCJR trellis structures for both binary and non-binary linear block codes.

    (b) From the flat fading channel simulations it was discovered that VA decoding of the binary cyclic $(5, 3, 2)$ code, using the reduced complexity BCJR trellis, exhibited an inferior performance to that obtained using the original BCJR trellis structure. However, this peculiarity can not be attributed to a deficiency in the reduced BCJR trellis structure, but rather to the fact that a non-systematic linear block code (which is a byproduct of the trellis reduction scheme) is slightly less able to minimise the bit error probability than a systematic equivalent. This is especially true for flat fading channels that generate bursty errors. Therefore, this phenomenon was negligible during the AWGN channel simulations and only took on measurable proportions during the flat fading channel simulations.

    (c) Results obtained during the flat fading channel simulations establish that fading amplitude CSI can easily be incorporated into the soft decision VA decoding of linear block codes that make use of reduced complexity BCJR trellis structures. For the binary cyclic $(5, 3, 2)$ linear block code, inclusion of fading amplitude CSI resulted in gains, ranging between 0.2 dB and 0.4 dB, over standard hard decision decoding for both the original and reduced BCJR trellis structures.

12. Conclusions from the simulated BER performance results for VA decoded interleaved binary Hamming $(7, 4, 3)$ and non-binary RS $(7, 5, 3)$ linear block codes, operating in varying fading channel conditions (see *Section* 6.5.5.1 and *Section* 6.5.5.2, respectively):

    (a) Performing channel interleaving proved to be beneficial to the BER performances of the VA decoded binary Hamming $(7, 4, 3)$ and non-binary RS $(7, 5, 3)$ linear block codes, operating in fading channel conditions. However, the improvements obtained were more drastic for the binary Hamming $(7, 4, 3)$ linear block code, since interleaving disperses error bursts, against which this code is ineffective.

    (b) In general, the BER performance improvements obtained by the addition of interleaving to coded narrowband communication systems, operating in flat fading channel conditions, increase as the maximum Doppler spread (i.e. fading rate) of the channel decreases. This can be explained by recalling that, for a fixed symbol rate, a decrease in maximum Doppler spread creates longer deep fades, resulting in lengthier error bursts. From this one can conclude that interleaving is best suited for slow fading channels.

    (c) Simulations performed with coded wideband complex DS/SSMA systems in multi-user multipath fading channel conditions revealed that interleaving is not only capable of improving the performance of the channel codes, but also alleviate the harmful effects of MUI, incited by high user loads in the CDMA system. One can therefore conclude that the MUI generated in the RAKE receiver structure considered in this study is not IID for each received and demodulated code bit, resulting in bursty errors that can be diffused using interleaving.

13. Conclusions from the simulated BER performance results for VA decoded punctured binary rate $R_c = 1/2$ RSC codes and binary BCH $(15, 7, 5)$ linear block codes, operating in varying mobile communication channel conditions (see *Section* 6.5.6.1 and *Section* 6.5.6.2, respectively):

    (a) Although the punctured binary 4-state, rate $R_c = 1/2$ RSC code of *Section* 6.5.6.1 has the same overall code rate as the binary 8-state, rate $R_c = 2/3$ RSC code discussed in *Section* 6.5.2.2, it produces inferior AWGN and flat fading channel BER performances. It is important to note, however, that the rate $R_c = 2/3$ RSC consistently outperformed the rate $R_c = 1/2$ code by 0.8 dB for hard decision VA decoding and 1.2 dB for soft decision VA decoding under all channel conditions considered. The punctured rate $R_c = 1/2$ RSC code's poor BER performance, however, is not the consequence of the puncturing procedure. This can be attributed to the code's small d_{free}. One can therefore conclude that the puncturing of binary RSC codes enables a code designer to accomplish rate adaptation, without severe losses in code performance.

    (b) For all channel conditions considered, soft decision VA decoding of the punctured binary BCH $(15, 7, 5)$ code delivered BER performances comparable to that of the soft decision VA decoded binary Hamming $(7, 4, 3)$ code. However, hard decision VA decoding of the punctured BCH code proved to consistently deliver BER performances inferior to that obtained through the hard decision VA decoding of the Hamming code. Recognising that the BCH $(15, 7, 5)$ code is far more powerful than the Hamming $(7, 4, 3)$ code, one can conclude that puncturing significantly degrades the BER performance of VA decoded linear block codes, especially when hard decision decoding is employed.

14. Conclusions regarding the BER performance improvements obtained by employing fading amplitude CSI during the soft decision VA trellis decoding of convolutional and linear block codes, operating in varying fading channel conditions (see *Section* 6.5):

    (a) The inclusion of fading amplitude CSI during the soft decision VA decoding of convolutional and linear block codes produced coding gains over standard soft decision decoding, ranging from 0.1 dB to 0.4 dB, depending on the code and channel conditions. Thus, if CSI estimation hardware/software is available in a linear block coded communication system operating in fading channel conditions, the system's BER performance can be marginally improved, without a profound increase in system complexity. However, if a CSI estimator is not implemented in the system, the increased system complexity might not justify the BER performance improvements obtainable through soft decision VA decoding with fading amplitude CSI.

    (b) In flat fading channel conditions, the gains achievable during the soft decision VA decoding of linear block codes by including fading amplitude CSI during the metric calculations, increase as the Rician factor or the fading rate (i.e. maximum Doppler spread) of the channel increases. Thus, using fading amplitude CSI during VA decoding is most effective for fast, Rician flat fading channels.

    (c) Using fading amplitude CSI during soft decision VA decoding yields more impressive BER performance improvements for linear block codes than for binary convolutional codes. From the simulation results obtained for the linear block codes considered in this study, it is clear that code complexity and strength has no influence on the BER performance improvements obtained by incorporating fading amplitude CSI during VA decoding.

   (d) Interleaving increases the BER performance improvements obtained by employing fading amplitude CSI during the soft decision VA decoding of linear block codes and binary convolutional codes. Conversely, performing puncturing impacts these gains negatively.
   (e) The multi-user multipath fading channel BER performance results show that the CSS family used and CDMA user load has no influence on the gains achievable by incorporating fading amplitude CSI during the soft decision VA decoding of linear block and binary convolutional codes, employed in wideband RAKE receiver-based DS/SSMA communication systems.
   (f) Using a reduced complexity BCJR trellis structure (see *Section* 4.3.2) during the soft decision VA decoding of a linear block code in fading channel conditions has no effect on the gains obtained by incorporating fading amplitude CSI in the metric calculations.

15. Conclusions relating to the temporal qualities, correlation properties, spectral characteristics and simulated BER performance results for the different CSS families considered in this study's DS/SSMA simulations (see *Chapter* 6 and *Appendix D*):

   (a) The multi-user multipath fading channel simulation results clearly reveal the superior BER performances of the unfiltered QPH and ZC CSS families over the pre-filtered ABC and DSB CE-LI-RU filtered GCL CSS families. For a fixed sequence length of $M_{seq} = 63$ chips, ABC sequences delivered the poorest BER performances of all of the CSS families considered in this study. Although the RU interpolation filtering techniques used to generate ABC and DSB CE-LI-RU filtered GCL CSSs (see *Section* D.3.2) reduce the spectral requirements of DS/SSMA systems employing these CSSs, the BER performance results lead one to conclude that these filtering approaches detrimentally influence the periodic correlation characteristics of CSSs, resulting in excessive MUI when used in CDMA systems. This observation is most evident for DS/SSMA systems employing ABC sequences, where the BER performances of RAKE receiver-based systems lag that of non-RAKE systems at high user loads, due to the self-noise generated in the RAKE receiver structures.
   (b) Although RU interpolation filtering has an unfavourable influence on the periodic correlation properties of CSSs, the resultant PSDs of DS/SSMA systems employing pre-filtered CSSs, such as ABC and DSB CE-LI-RU filtered GCL CSSs, exhibit desirable characteristics. This study corroborated the findings of [4], demonstrating that ABC and DSB CE-LI-RU filtered GCL CSSs exhibit PSDs with cutoff rates only obtainable through Nyquist roll-off factor $\varsigma = 0$ filtering. Furthermore, ABC sequences generate spectrally economic SSB signals. Thus, using pre-filtered CSSs in DS/SSMA communication systems not only simplifies the wideband transmitter structures by removing the need for chip shaping filters, but also minimises the co-channel and adjacent channel interference [42, 47] encountered in cellular mobile networks. One can therefore conclude that the use of pre-filtered CSSs in future wideband B3G and 4G cellular DS/SSMA systems, will greatly simplify cell planning.
   (c) Notwithstanding the fact that the maximum number of users supported by a DS/SSMA system is limited by MUI, it is mainly a function of the number of unique sequences available to be assigned to users. In turn, the number of unique sequences is largely dictated by the sequence length M_{seq} of the spreading sequence family used. Due to their superior SSLDs, the use of ABC and DSB CE-LI-RU filtered GCL CSSs enable the communications engineer to select sequences that are longer in length than QPH and ZC CSSs, but occupy an equivalent transmission bandwidth. Furthermore, using longer spreading sequences not only increases the number of possible users in the CDMA system, but also improves the system's MUI levels, since the periodic correlation characteristics of spreading sequences improve as their lengths increase.
   (d) The investigation into the influence of the CSS selection approach on the multi-user multipath fading channel performance of an uncoded RAKE receiver-based complex DS/SSMA system,

employing length $M_{seq} = 63$ ABC sequences, shows that CSSs can not be arbitrarily chosen from the available set of sequences, if an optimal multi-user BER performance is desired. From the simulation results one can conclude that the proposed CSS selection approach of *Section* 6.5.1.3.2 is an efficient method whereby sequences can be selected from a GCL CSS [9] family, such that the mutual periodic correlation characteristics of the chosen CSSs are optimal.

This study demonstrated the dexterity of the block-wise VA as an eloquent MLSE detection technique, which can be used to accomplish perfect hard or soft decision ML trellis decoding of any type of binary or non-binary linear block code. Hence, when applied to the BCJR trellis structures of linear block codes, the VA equips the communications engineer with a single generic linear block code decoding algorithm, eliminating the quintessential need to implement code-specific decoding algorithms, such as the Berlekamp Massey algorithm. The theoretical analyses, novel algorithms, extensive performance evaluation platforms and simulation results presented in this study, expedite further research and development of generic SISO trellis-based decoding algorithms, capable of efficiently and optimally decoding convolutional codes, linear block codes and concatenated codes, all of which will conceivably be included in adaptive channel coding schemes for future wireless narrowband and wideband mobile communication systems.

7.3 FUTURE RESEARCH

This study touched on a broad variety of fields within digital communications, ranging from channel modelling and channel coding, to the development of simulation platforms. As such, several avenues for future research were identified. Only those prospective research areas where meaningful results and applicability to current and future communication systems seem to be forthcoming, are listed below:

1. From *Section* 3.3.5, it is clear that channel estimation remains an extremely active research field. The use of CSI in ML and MAP decoding schemes in order to improve BER performances, has become mainstream in most new developments in channel coding. However, chasing *Shannon*'s channel capacity limit [1, 13, 62] will remain a purely academic exercise, without commercial applicability, as long as practical and implementable CSI estimation techniques are lacking.

2. Although the novel complex flat and multipath fading channel simulator models presented in *Section* 2.6.2.3 and *Section* 2.6.3.2, respectively, are capable of adequately reproducing the statistical nature of real life mobile fading channels, they fall short in two aspects: Firstly, after initialisation the flat fading channel simulator is only capable of creating a fixed maximum Doppler spread. This can be improved by employing adaptive Doppler spread spectral shaping filters, instead of the fixed IIR filter structure of *Section* 2.6.2.4.2. Secondly, the complex multipath fading channel simulator is currently only capable of producing stationary channel characteristics (see *Section* 2.4.1), due to the use of fixed path delays. This model can be improved to also support non-stationary channels by simply incorporating time-variant path delays.

3. A SOVA decoder [16, 61, 165, 166] that can be used as a SISO decoder [87, 91] module for linear block codes, is an attractive proposition. Such a decoder will become an invaluable building block in classic and iteratively decoded concatenated coding schemes employing linear block codes. The original SOVA algorithm, developed by *Hagenauer* [61], as well as derivatives thereof, are aimed at the decoding of convolutional codes. The author of this dissertation has since attempted to develop a block-wise SOVA that can operate on linear block codes' BCJR trellises. Unfortunately, only partial success has been achieved with a viable SOVA for systematic binary linear block codes.

4. The use of trellis decoded linear block codes as CCs (alongside current RSC and NSC CCs) in future iteratively decoded concatenated coding schemes, might result in elegant concatenated encoder structures that will not fall victim to the ever present trellis termination [167–169] dilemma. In a classic TC [89] encoder, using for argument's sake RSCs C_1 and C_2 as the respective CCs, the input data bits encoded by encoder C_1 are interleaved before they are processed by C_2. However, the data bits encoded by C_1 usually contain termination bits that will ensure trellis termination for its associated SISO trellis decoder [170]. Unfortunately, these termination bits are also interleaved, leaving the trellis of encoder C_2 unterminated. This leads to inefficient iterative decoding and is partially responsible for the characteristic floors [66, 68, 92] observed in the measured BER performance results of TCs. To combat this problem in classic concatenated coding schemes, constructed using convolutional codes as CCs, two options are available: Firstly, try to design [168, 171] the interleaver such that all CCs terminate in a known state. Secondly, use extremely long input messages, thereby minimising the effect of incorrect decoding at the termination bit positions. The first option limits the concatenated code designer's selection of possible interleaver structures, usually resulting in interleaver gains [19, 88] inferior to those that could have been achieved using s-random interleavers (see *Section* C.3.3). The second option, although effective, limits the use of powerful iteratively decoded concatenated coding schemes to data sources which are not delay sensitive, i.e. data sources other than realtime voice or video. Recalling from *Section* 4.2 that the BCJR trellis of a linear block code always terminates in state $(0, n)$, implies that trellis termination will not be a concern for concatenated coding schemes using linear block codes as CCs. It also makes the use of iteratively decoded concatenated coding schemes for short frame transmission viable. However, linear block codes do not exhibit the recursive nature required [19, 88] by PCC schemes, making it safe to assume that linear block codes as CCs will most likely find application only in SCCs [27, 28, 30, 31] and HCCs [30, 33].

5. The trellis decoding of non-linear block codes is a research field that has remained largely untouched. Contributions that can be made to this field include the design of trellis construction algorithms, similar to the BCJR trellis generation algorithm for linear block codes (described in *Section* 4.2), as well as possible trellis reduction techniques.

6. *Section* 5.4.3 presented a realistic multi-user multipath simulation platform, based on the wideband complex DSSS/MA QPSK communication system of *Section* 5.3. This CDMA platform utilises the CSS families detailed in *Appendix D*. In this study, only VA decoded classic convolutional and linear block coding schemes were tested on this platform. This still leaves room for experimentation with concatenated coding schemes (classic and iteratively decoded), *Space Time Code*s (STC), *Multi-Level Code*s (MLC), LDPCs and many others on this B3G [45] platform.

7. *Turbo Product Codes* [172] consist of two linear block codes, which simultaneously encode the rows and columns of a two-dimensional block of information symbols. Decoding is accomplished by processing the row and column encoded symbols with separate iterative ML or MAP SISO decoder modules, which exchange a-priori information on the decoded information symbols during each iteration. These concatenated block codes, considered to be one step down from TCs on the evolutionary ladder of channel coding schemes, have become the most prevalent iteratively decoded concatenated coding scheme in commercial digital communication systems, due to their simplicity and TC-like potency. However, the iterative ML and MAP decoding approaches thus far proposed [172–174], still make use of brute force code book searches. As such, employing trellis decoding techniques for linear block codes might be an interesting proposition to investigate. Furthermore, the construction of multi-dimensional trellis structures that simultaneously represent two or more linear block code CCs in a block product code, is also an interesting untapped field for future research.

”For years radios had been operated by means of pressing buttons and turning dials; then as the technology became more sophisticated the controls were made touch-sensitive - you merely had to brush the panels with your fingers; now all you had to do was wave your hand in the general direction of the components and hope. It saved a lot of muscular expenditure of course, but meant that you had to sit infuriatingly still if you wanted to keep listening to the same programme.” [1]

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[1] *Source: ”The Hitch Hiker’s Guide to the Galaxy,” by Douglas N. Adams, 1985*