PART I

OVERVIEW OF THE DSSS COMMUNICATION SYSTEM

CHAPTER ONE
INTRODUCTION AND OVERVIEW

This chapter provides an overview of the DSSS communication system employing complex spreading sequences presented in this dissertation. The first sections of this chapter give an introduction as well as the main objectives of the dissertation. This is followed by the outline of the dissertation illustrated by a schematic representation. The contributions of this research and development are discussed and the chapter is then concluded with an overview of a generic DSSS system.

1.1 OVERVIEW OF THE GENERIC DSSS SYSTEM

The use of DSSS techniques in communication systems has grown considerably over the past decade. This is because CDMA is considered a promising technique to obtain high spectral and power efficiency (low fading margin) in multiple-access applications, such as for example in personal communication networks (PCN), in addition to its well-known merits in the field of secure communications. A DSSS system employing complex spreading sequences may include several additional advantages [1], [2], [3], such as offering a perfectly constant envelope output signal, including the possibility to generate a SSB DSSS signal with theoretically up to $6dB$ more PG than offered by conventional DSB systems, while still exhibiting comparable auto and improved cross correlation properties compared to any other (binary) DSSS schemes presently employed [4].

This dissertation describes the theoretical analysis [5–8] of a novel DSSS transmitter and receiver structure employing complex spreading sequences. The structure is generic in the sense that it can be employed in many different ways, i.e., in a balanced QPSK configuration [1] or in a normal dual-channel QPSK configuration [2] by using most of the common multi-amplitude multi-phase (QAM) modulation strategies. The output signal of the transmitter is generated by means of complex multiplication of the input data, the complex spreading sequences and the quadrature carriers and by finally taking the real part of the result. The receiver structure is responsible for demodulation and despreading of the received DSSS signal. Diversity is built into the system by utilizing a balanced mode of operation. In the balanced mode of operation, when either the in-phase or quadrature-phase components of the signal is eliminated during transmission, the original data can still be recovered from the remaining signal component.

A description of the complex spreading sequences with their properties will be given, as well as simulation results of the system employing these complex sequences [9]. The simulation results will include both the double side band (DSB) and single side band (SSB) cases, which both provides constant output signal envelopes [10]. Another advantage of using chirp-like complex spreading sequences is the fact that they can be band limited by means of novel mod-π or analytical mod-2π root-of-unity filtering processes, while still maintaining a perfectly constant envelope output signal.

The theoretical analysis will then be used as a basis for the practical implementation of the system. A brief description of the operation of the practical system will be given, as well as practical results obtained from a generic hardware implementation of the DSSS communication link.

The DSSS system provides a choice of data rates by selecting different families and lengths of spreading sequences for a given chip rate and transmission bandwidth. A minimum PG of at least 10 dB is maintained throughout, although PGs of more than 30 dB are feasible. The proposed DSSS system may be readily expanded to serve a multi-user CDMA-DSSS environment. This is however not incorporated into this dissertation, but left as a future exercise.

1.2 MAIN OBJECTIVES

The main objective of this dissertation is the hardware implementation of a prototype two-dimensional (QPSK) DSSS baseband modem employing complex spreading sequences, including all synchronisation subsystems necessary to achieve coherent DSSS

[1] Balanced operation implies that the input data stream is duplicated on the in-phase (I) and quadrature phase (Q) branches prior to modulation onto quadrature carriers.

[2] Dual-channel operation implies that the incoming data is serial-to-parallel converted into two quadrature half rate symbol streams prior to quadrature modulation.

communication. Although the modulation principles presented may be extended to more than two dimensions, this will be specifically reserved for future research. A detailed design and analysis of the DSSS system are two of the primary objectives of this study. The study will mostly focus on the performance of the system in the AWGN channel, although some simulation results will be presented to illustrate the operation of the system under fading channel conditions, as well as in the presence of a number of users sharing the same bandwidth. Multi-user detection, cancellation and RAKE-combining have however been explicitly excluded from the hardware design as a result of the complexity of the project as it stands. These aspects are also the objectives of a companion dissertation. Some multi-user results under various Rayleigh-fading mobile channel conditions will nevertheless be presented for comparison purposes, where appropriate. The implementation of the new DSSS communication system involved the analysis and design of unique synchronization loops for code tracking and carrier phase estimation, as a result of the use of complex spreading sequences. Extensive analytical analysis and theoretical as well as simulation results will be presented to verify correct operation of all subsystems, as well as the complete DSSS system, including the RF-link. The latter subsystem

The dissertation objectives can be summarized as follows:

- Theoretical design and analysis of a DSSS communication system employing complex spreading sequences.
- Simulation of a DSSS wireless communication link employing complex spreading sequences.
- Design of implementation structures for the transmitter and receiver of a DSSS communication system with complex spreading sequences, employing appropriate (FPGA) implementation technologies.
- Design and realisation of implementation technologies for the synchronization of timing (code, bit and frame synchronisation) and carrier frequency and phase estimation of a DSSS communication system employing complex spreading sequences.
- Simulation and prototype hardware performance evaluation of the DSSS system under typical AWGN and some fading mobile channel conditions, including power saturation effects.

1.3 DISSERTATION OUTLINE

Figure 1.1 contains a schematic representation of this dissertation.

The dissertation is outlined as follows:

PART I gives an overview of the DSSS communication system in Chapter 1.

A theoretical analysis is presented in *PART II* and is consisting of Chapter 2 to Chapter 6. Chapter 2 gives the theoretical background of SS systems. Chapter 3 describes the complex spreading sequences and their properties, e.g. auto and cross-correlation properties. The analysis of the DSSS transmitter is presented in Chapter 4. Both balanced QPSK and a conventional dual channel QPSK transmitter structures have been investigated, employing unique combinations of the real and imaginary parts of the complex spreading sequences. The DSSS receiver is analyzed in Chapter 5. Different receiver structures were investigated in the search for an optimum configuration for the proposed DSSS communication system, employing complex spreading sequences. The receiver structures have been designed to demodulate and despread transmitter signals corresponding to the balanced and dual-channel transmitter configurations, respectively. In Chapter 6 the synchronization of the DSSS communication system is investigated. Code acquisition, code tracking and carrier synchronization techniques for best system performance are described. Synchronization structures for code acquisition and code tracking as well as carrier tracking and data demodulation are investigated and designed by using a coherent approach for a DSSS system employing complex spreading sequences. A combined coherent Decision-Directed Costas Carrier Recovery Loop (DD-CCRL) and Coherent Decision-Directed Complex Delay-Lock-Loop (DD-CDLL) synchronization scheme for a DSSS communication system, originally proposed by De Gaudenzi for systems using binary spreading sequences, have been generalized and extended to include systems employing binary and/or complex spreading sequences. The advantages offered by this unique code locking scheme are also discussed.

PART III presents the DSSS system simulation. Simulation of the complete complex DSSS communication system, as designed and analyzed in Chapters 4, 5 and 6, were done prior to hardware implementation, in order to evaluate and verify correctness of the theoretical design. In Chapter 7 the simulation of the DSSS transmitter, employing complex spreading sequences, is done. In Chapter 8 the simulation of the receiver with all corresponding results are presented. The decision-directed complex Costas carrier recovery loop, decision-directed complex DLL as well as the acquisition circuitry are also simulated to perform a fully independent receiver structure responsible for code acquisition, carrier

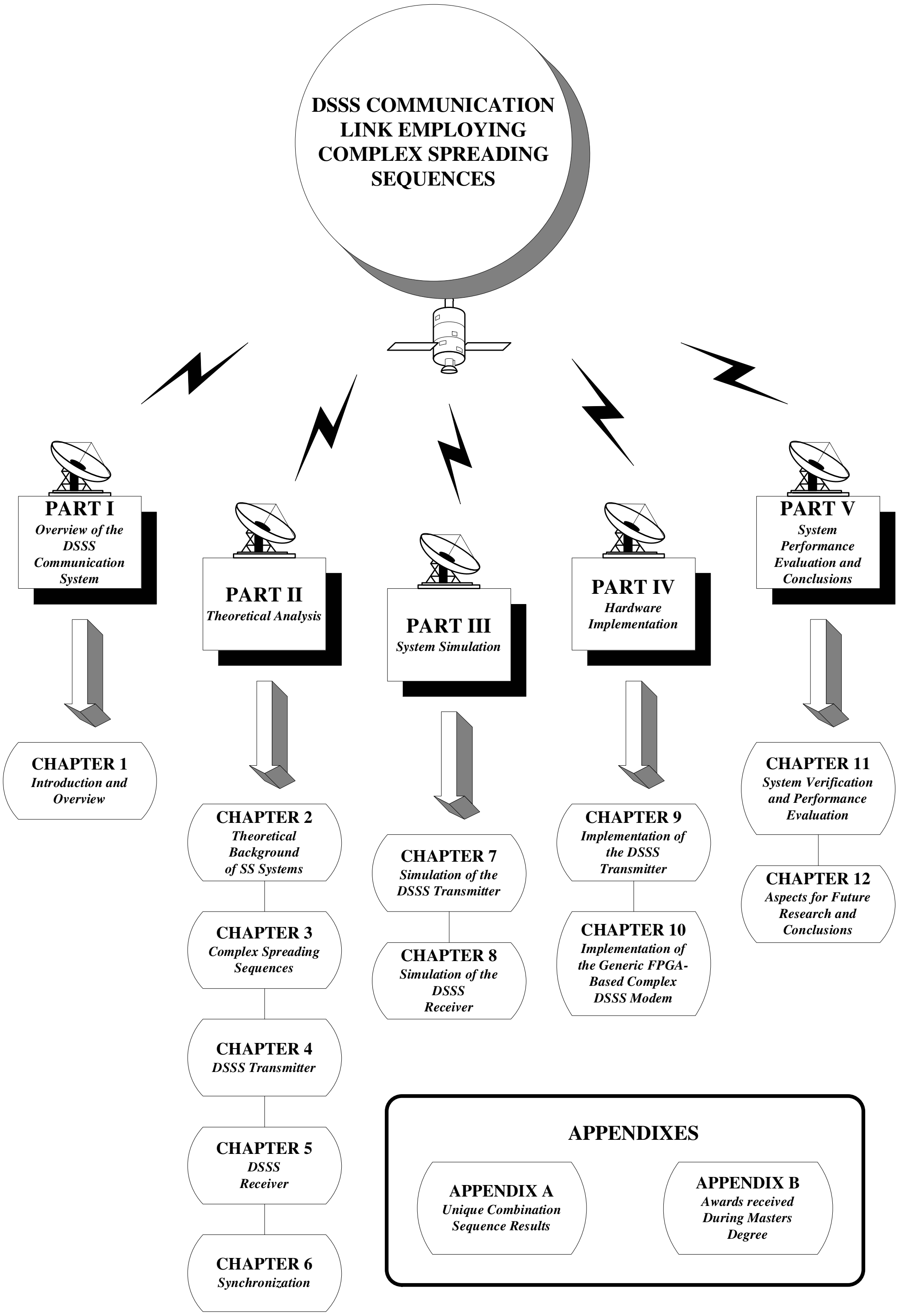

FIGURE 1.1: Schematic representation of the dissertation outline

recovery and code tracking. Results related to these loop structures are also given.

PART IV contains the hardware implementation of the DSSS system. Chapter 9 gives the design approach and hardware transmitter structures used, as well as results obtained with this transmitter module. The transmitter module was the first prototype version built to illustrate the practical implementation of complex spreading sequences. The results obtained with the hardware transmitter module correlated very well with the theory and simulations. The system was also upgraded to a more advanced version on FPGA technology and is also described in detail. In Chapter 10 the final FPGA-based complex DSSS modem is presented, which is a great improvement in terms of technology relative to the structures described in Chapter 9. In Chapter 10 the aforementioned theoretical structures and schemes were implemented in hardware by utilizing Altera's FPGA technology. IF sampling principles were applied at the receiver and implemented on FPGA using VHDL programming software, resulting in a number of advantages compared to analog down-conversion and carrier tracking. The hardware results of the complex DSSS communication system are presented in this chapter. Complete system specifications are presented, as well as a brief description of the operation of the DSSS system.

PART V gives a system performance evaluation and conclusion. Chapter 11 presents the system verification and performance evaluation. This chapter compares the system performances of the balanced and dual channel DSSS QPSK modulation configurations, employing a class of constant-envelope root-of-unity (CE-RU) filtered complex spreading sequences, with conventional Nyquist filtered QPSK modulated CDMA systems employing binary spreading sequences. A verification and performance evaluation of the balanced and dual channel DSSS QPSK system employing CSS are presented in terms of bit error rate performance, spectral and power efficiency, transmitter output peak-to-average power ratio (PAPR), etc. The comparison is also done in non-linear power amplification and is based on Complementary Cumulative Probability Density Function Peak-to-Average Power Ratio (CCDF-PAPR) measurements, as well as the amount of spectral regrowth experienced when the power amplifier is driven close to the so-called 1dB saturation point. Simulation as well as hardware results are presented to illustrate the superiority of the new complex-spreaded WCDMA modulation schemes over conventional methods in terms of spectral and power efficiency in the presence of non-linear power amplification. Chapter 12 gives the aspects for future research and concludes with the main objectives of the dissertation. In this chapter the ultimate goal of this research project is given, that was to design and develop a generic DSSS modem employing complex spreading sequences (CSS). This objective has been achieved with the establishment of a prototype WLL RF-link, providing the required vehicle and test bed to verify and illustrate all the principles and concepts formulated, e.g., the concept of linear root-of-unity filtering and its realisation in hardware.

Appendix A and B presents the results of the unique combination sequences as well as the awards received during Masters degree, respectively.

1.4 TYPICAL APPLICATIONS OF THE PROPOSED NEW DSSS COMMUNICATION SYSTEM

The generic DSSS communication system presented in this dissertation may typically form the heart of both limited coverage ('small-area') as well as large coverage ('wide-area') applications. In a small-area application, the system may coexist with other services with minimum interference, due to its small footprint (micro- to pico-cellular, i.e., for example, in 100m radius application scenarios), exceptionally low emission power levels and the fact that DSSS is in effect a low-probability-of-intercept (LPI) concept (i.e., will cause minimum interference with co-users in the same frequency band), while it is capable of suppressing in-band interference by virtue of its inherent Spreading or Processing Gain (PG) (which may be in access of 30dB, depending on the available bandwidth).

Possible secondary small-area applications that has already been touched on in the introduction, is the application of the proposed concepts as a semi-mobile extension to existing PABX technologies, giving the latter 'fixed' services an extra mobility dimension whereby the users are allowed to roam about within a predefined coverage area (typically micro-cellular, such as would be found within a building). The same Wireless-Local-Loop (WLL) concept could naturally be applied in a host of other applications, such as in cases where temporary telecommunications must be established over a limited period of time (e.g., at conferences, sport events etc.). Another major small or wide-area application could be in remotely situated rural areas where both small and densely populated communities could be given affordable local multimedia telecommunication services (including digital speech, data and video), via standard interfaces and high capacity links (e.g., microwave, satellite link, optical fibre) to not only the PSTN, but also to existing cellular and Internet infrastructures. The development of such an affordable multimedia CDMA product is presently the topic of an NRF-supported research and development (R&D) programme. In addition, a two-dimensional application of the novel DSSS techniques presented in this dissertation, have found application in a ultra-high distance telemetry control link, which has to date outperformed all other competing solutions in this field of application.

Moreover, an extension of the proposed new modulation technique to more than four dimensions would allow the establishment of WLAN ’last-mile’ access systems, whereby customers may be offered multimedia broadband Internet access. One way to achieve the latter goal is to use techniques similar to that of WiMax, utilising a novel multi-dimensional configuration (using more than four dimensions) with interesting similarities to OFDM modulation schemes (but with significantly better power efficiency and superior performance), to realise a form of IP-based broadband WLAN service, which may render an alternative to present 2 and 3G wireless cellular services. Since the proposed multi-dimensional modulation concept may be extended to offer very high data throughput rates at practically the performance of a conventional QPSK modulation system, it may even be considered for application in fourth generation (4G) wireless cellular applications.

The proposed micro-cellular system, incorporating the generic DSSS transmitter, will not only be easy to deploy, but also relatively efficient in terms of power (i.e., battery) requirements, due to its near constant envelope (i.e., instantaneous power) output. The latter advantage will obviously have a direct impact on terminal costs, due to the reduced transmitter power requirements of the handsets, compared to for example contending existing TDMA techniques. Since the power source and high power amplifier subsystems may contribute as much as 20% of the total handset cost, significant savings may be incurred by employing the DSSS system with complex spreading proposed in this dissertation. The unique multidimensional DSSS modulation scheme offers flexible data rates within relatively small spreading bandwidths, while maintaining high processing gains - the necessary ingredients to provide for ’service-on-demand’ multi-media requirements.

1.5 MAIN CONTRIBUTIONS

The advantages and applications outlined above are based on major contributions that evolved from this research and prototype hardware development, including the following:

- Unique upwards-expandable multi-dimensional transmitter and receiver configurations are proposed employing complex spreading sequences.

- Novel carrier synchronization techniques are presented, in order to overcome the presence of unwanted interference terms in the process of achieving carrier phase estimation in the presence of complex spreading.

- Similarly, dedicated code tracking loops have been proposed, designed and analyzed, capable of tracking the chip timing of the desired received DSSS signal's complex spreading code.

- The superior performance (compared to existing binary DSSS systems) of the latter synchronisation subsystems, including the complex detection process, can be attributed to using unique combinations of the real and imaginary parts of the complex spreading sequence allocated to individual users.

- The proposed new generic DSSS system is sufficiently versatile to allow the use of either binary or complex spreading sequences.

- One major contribution is the use of families of Non-Linearly-Interpolated Root-of-Unity (NLI-RU) filtered complex spreading sequences capable of producing constant-envelope Double-Side-Band (DSB), as well as Single-Side-Band (SSB) DSSS outputs. To the author's knowledge, no comparable constant-envelope results have ever before been produced for SSB modulation systems.

- Sequences (binary as well as complex) may be pre-NLI-RU-filtered before being downloaded to the DSSS transmitter. Surprisingly tightly filtered output signals can be obtained by employing the NLI-RU filtering method, requiring only mild additional bandlimiting to meet RF-mask requirements in most cases.

- NLI-RU filtered complex spreading sequences exhibit perfectly constant envelope, even with SSB modulation, giving systems employing these sequences a definite power efficiency advantage compared to non-constant envelope schemes.

- The generic DSSS transmitter is very flexible in terms of data rate, spreading sequence length and Processing Gain (PG). Not only can different multi-phase as well as multi-amplitude modulation techniques be very easily implemented, but the system may be easily adapted to serve a host of variable data rate ('service-on-demand') applications, some of which have been outlined above.

- Lastly, the above mentioned subsystems have been implemented in reprogrammable FPGA hardware, resulting in the generation of considerable intellectual property (IP) in the form of additional DSSS/CDMA VHDL functional core software.

1.5.1 List of Publications

- F.E. Marx and L.P. Linde, ”DSP implementation of a generic DSSS transmitter employing complex or binary spreading sequences”, *COMSIG’95*, pp 75-80, 16 November 1995.
- F.E. Marx and L.P. Linde, ”DSP implementation of a generic DSSS transmitter”, in *Elektron, Journal of the South African Institute of Electrical Engineers*, pp 20-22, March, 1996.
- F.E. Marx and L.P. Linde, ”Theoretical analysis and practical implementation of a balanced DSSS transmitter and receiver employing complex spreading sequences”, in *Proceedings of AFRICON’96*, pp 402-407, University of Stellenbosch, Stellenbosch, 22-24 September, 1996.
- F.E. Marx, M. Snyman, M. Drewes, R. Milton and F.M. Ragghianti, ”Measurements for digital telecoms channels”, in *Elektron, Journal of the South African Institute of Electrical Engineers*, pp 47-49, April, 1998.
- F.E. Marx and L.P. Linde, ”A combined coherent carrier recovery and decision-directed delay-lock-loop scheme for DS/SSMA communication systems employing complex spreading sequences”, in *Proceedings of the IEEE International Symposium on Spread Spectrum Techniques and Applications, ISSSTA’98*, Sun City, South Africa, September 1998.
- F.E. Marx and L.P. Linde, ”A combined coherent carrier recovery and decision-directed delay-lock-loop scheme for DS/SSMA communication systems employing complex spreading sequences”, *The Transactions of the SAIEE Special Issue: CDMA Technology Changing the face of wireless access*, Vol. 89, No. 3., pp 131-139, September 1998.
- F.E. Marx and L.P. Linde, ”Four Dimensional Modem Employing Complex Spreading Sequences”, in *Proceedings of AFRICON’99*, pp 221-226, Cape Technicon, Cape Town, September, 1999.
- F.E. Marx and L.P. Linde, ” A Novel Four Dimensional Modem for Wireless Multimedia Communications”, in *Proceedings of the IFAC Conference on Technology transfer in Developing Countries: Automation in Infrastructure Creation, IFAC DECOM - TT 2000*, pp 212-217, Pretoria, South Africa, July 2000.

- L.P. Linde, F.E. Marx and W.R. Malan, ”Power and spectral efficiency of a family of constant-envelope root-of-unity filtered complex Spreading Sequences in WCDMA non-linear power amplification”, in *Proceedings of AFRICON'02*, pp 395-400, George, South Africa, October, 2002.
- J.F. Pienaar, L.P. Linde and F.E. Marx, ”Realization of multi-level partial response modem in reconfigurable logic”, in *Proceedings of AFRICON'02*, pp 167-172, George, South Africa, October, 2002.
- L.P. Linde and F.E. Marx, ”Power and spectral efficiency performance of a family of WCDMA-modulated constant envelope root-of-unity filtered complex spreading sequences in non-linear power amplification”, *The Transactions of the SAIEE: Research Journal of the South African Institute of Electrical Engineers*, Vol. 94, No. 4., pp 57-67, December 2003.

1.5.2 List of Patents

- L.P. Linde and F.E. Marx, ”Multi-Dimensional Spread Spectrum Modem”, South African Complete Patent no. 2000/2645, 30 January 2002. (Earliest priority claimed: ZA 99/1136, dated 26-02-1999).
- L.P. Linde and F.E. Marx, ”Multi-Dimensional Spread Spectrum Modem”, United States Complete Patent no. 6,744,807, 1 June 2004.

1.5.3 List of Awards

- F.E. Marx and L.P. Linde, SABS design institute awards, 1996.
- F.E. Marx, Special Merit Award of the SAIIPL, 1996.
- L.P. Linde, D.J. van Wyk, B. Westra, F.E. Marx and W.H. Büttner, SABS design institute awards, 1997.

1.5.4 Potential Applications and Products

The new DSSS technology presented in this dissertation, has already found several practical and real-world applications, some of which are mentioned below.

- The generic DSSS transmitter has firstly been used by the CSIR in a channel sounding application to measure the delay-spread profile of typical wireless communication channels at different carrier frequencies. Such a wideband DSSS transmitter can be used in various similar applications, e.g. in different types of channel sounding, accurate distance and signal path delay measurements, radar applications and many more.

- As a second example, an appropriately adapted version of the wireless DSSS communication system was in fact employed in a specialised commercial application. The particular application comprised a long distance ($>$ 200 km) ultra wide-band DSSS equivalent of the prototype DSSS system, capable of meeting all the stringent requirements specified for this particular project, including low probability of interception (LPI) operation and synchronisation in the presence of adverse (sub-zero dB SNR) conditions. Since the DSSS communication link used the technology and principles presented in this dissertation, it therefore serves as a realistic test bed and confirms and verifies the analysis and evaluation results presented in this dissertation.