UNIVERSITY OF SOUTHAMPTON
FACULTY OF PHYSICAL SCIENCES AND ENGINEERING
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Reduced-Complexity Communications System Design

by

Chao Xu
B. Eng., B.Sc.(Eng.), MSc.

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SUPERVISOR:
Professor Lajos Hanzo
FREng, FIEEE, FIEE, DSc, EIC IEEE Press
Chair of Communications, Signal Processing and Control Group
and
Dr Soon Xin Ng
PhD, SMIEEE, MIET, CEng, FHEA
Department of Electronics and Computer Science
University of Southampton
Southampton SO17 1BJ
United Kingdom

Dedicated to my parents, Professor Jingxia Zhang and Mr Zucheng Xu and to my grandparents who would have been proud to live to see this treatise.

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

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Doctor of Philosophy

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The technical breakthrough of Turbo Codes (TCs) initiated two decades of exciting developments leading to a suite of near-capacity techniques. It has been widely recognized that exchanging extrinsic information between the channel decoders and the modulated signal detectors assists communications systems in approaching their best possible performance potential that is predicted by the channel capacity. Nonetheless, in line with Moor's Law, as researchers inch closer and closer to the channel capacity, the complexity of the resultant communications systems is also significantly increased. In fact, soft-decision-aided signal detection conceived for Single-Input Single-Output (SISO), Single-Input Multiple-Output (SIMO) and Multiple-Input Multiple-Output (MIMO) schemes typically contribute a substantial fraction of the total complexity, especially when multiple received samples have to be jointly detected in order to combat the deleterious effect of channel fading. Against this background, in this treatise, we firstly propose a reduced-complexity design for the classic soft-decision-aided PSK/QAM detectors, and then these reduced-complexity design guidelines are applied to a variety of communications systems spanning from coherent to noncoherent, from uncoded to coded, and also from SISO to MIMO systems. Our aim is to reduce the computational complexity as much as possible, especially for complex near-capacity communications systems, while mitigating any performance loss imposed by our reduced-complexity design.

First of all, we commence from the family of basic coherent SISO/SIMO systems, where both uncoded and coded PSK/QAM schemes are considered. The channel coding assisted near-capacity systems design principles are introduced based on EXtrinsic Information Transfer (EXIT) charts. Furthermore, we observe that the Max-Log-MAP algorithm invoked for soft-decision-aided PSK/QAM detection aims for finding the maximum probabilities, which is similar to the action of hard-decision-aided detection of uncoded *M*PSK/QAM schemes. Therefore, we propose to link each *a priori* LLR to a reduced-size fraction of the channel's output signal constellations, so that the Max-Log-MAP algorithm may be operated at a reduced complexity. Moreover, the corresponding reduced-complexity Approx-Log-MAP algorithm is also conceived by compensating for the Max-Log-MAP algorithm's widely-used Jacobian approximation relying on a lookup table. Our performance results demonstrate that up to 41.6% and 72.6% complexity reductions are attained for soft-decision-aided Square 64QAM and Star 64QAM detectors, respectively, which is achieved *without any performance loss*. This complexity reduction is substantial, especially when the soft-decision-aided signal detectors are invoked several times during turbo detection.

Secondly, we proceed by conceiving reduced-complexity algorithms for the noncoherently detected DPSK schemes in both uncoded and coded SISO/SIMO systems. More explicitly, the DPSK transmitter modulates the data-carrying symbols onto the phase changes between consecutive transmitted symbols, so that the Conventional Differential Detection (CDD) may recover the source information by observing the phase change between every pair of consecutive received samples. However, the CDD aided DPSK suffers from a 3 dB performance penalty compared to its coherent counterpart. Moreover, an irreducible error floor occurs, when the CDD is employed in rapidly fluctuating fading channels. In order to mitigate this problem, Multiple-Symbol Differential Detection (MSDD) may be invoked in order to improve the DPSK performance by extending the observation window length from the CDD's $N_w = 2$ to $N_w \geq 2$. The price paid is that the MSDD complexity grows exponentially with $(N_w - 1)$ as a result of jointly detecting the $(N_w - 1)$ data-carrying symbols. As a remedy, the Decision-Feedback Differential Detection (DFDD) concept may be introduced in order to detect a single symbol based on previous decisions concerning the $(N_w - 2)$ data-carrying symbols in a MSDD window. However, the DFDD inevitably imposes a performance loss due to its inherent error propagation problem. In order to retain the optimal MSDD performance, the Multiple-Symbol Differential Sphere Detection (MSDSD) facilitates the MSDD by invoking a Sphere Decoder (SD). Against this background, we firstly propose to introduce a simple correlation operation into the hard-decision-aided MSDSD employing an arbitary number of Receive Antennas (RAs), so that the SD may visit the constellation points in a zigzag fashion for the case of uncoded DPSK SIMO systems. Furthermore, we propose a reduced-complexity Schnorr-Euchner search strategy for the soft-decision MSDSD employing an arbitrary number of RAs, so that the optimum candidate may be found by visiting a reduced-size subset of constellation points, and then the rest of the constellation points may be visited in a zig-zag fashion. Our simulation results demonstrate that up to 88.7% complexity reduction is attained for MSDSD $(N_w = 4)$ aided D16PSK. We have also proposed the near-optimum Approx-Log-MAP algorithm conceived for soft-decision-aided SD, which has not been disseminated in the open literature at the time of writing. Furthermore, the important subject of coherent versus noncoherent detection is discussed in the context of coded systems, which suggests that MSDSD aided DPSK is an eminently suitable candidate for turbo detection assisted coded systems operating at high Doppler frequencies.

Following this, a range of noncoherent detectors designed for non-constant modulus Differential QAM (DQAM) schemes are introduced for both uncoded and coded scenarios, where the open problem of MSDSD aided Differential QAM (DQAM) is solved. More explicitly, the MSDSD relies on the knowledge of channel correlation, which is determined both by the Doppler frequency and by the noise power. For DPSK, the transmitter's phases may form a unitary matrix, which may be separated from the channel's correlation matrix, so that a lower triangular matrix that is created by decomposion from the inverse of the channel's correlation matrix may be utilized in the context of sphere decoding. However, for DQAM, the transmitted symbol-amplitudes cannot form a unitary matrix, which implies that they have to be taken into account by the channel's correlation matrix. As a result, the symbol-amplitude-dependent channel correlation matrix only becomes

known, when all the symbol-amplitudes are detected. Furthermore, the classic DFDD solutions conceived for DQAM rely on the assumption of the channel's correlation matrix being independent of the symbol-amplitudes, which implies that these DFDD solutions are sub-optimal and they are not equivalent to the decision-feedback aided version of the optimum MSDD. To circumvent these problems, we prove that although the complete channel correlation matrix remains unknown, the associated partial channel correlation matrix may be evaluated with the aid of the SD's previous decisions as well as by relying on a single information-dependent symbol amplitude that may be readily found by the SD. As a benefit, we are able to invoke sphere decoding for both amplitude detection and phase detection in the context of MSDD aided DQAM. Furthermore, we have also improved the classic DFDD solutions conceived for DQAM by directly deriving them from the optimum MSDD. Moreover, we offer a unified treatment of diverse noncoherent detectors, including CDD, MSDD, MSDSD and DFDD for a variety of DQAM constellations that exist in the literature, including Differential Amplitude Phase Shift Keying (DAPSK), Absolute-Amplitude Differential Phase Shift Keying (ADPSK) and their twisted constellations. The reduced-complexity algorithms proposed for DPSK detection are also applied to DQAM detection in both uncoded and coded systems .

Last but not the least, we provide insights concerning the design of MIMO systems in both uncoded and coded scenarios, where two of the salient tradeoffs encountered in MIMO system design are investigated. Firstly, the tradeoff between the attainable multiplexing and diversity gain of MIMO schemes is discussed. More explicitly, the V-BLAST MIMO systems have a capacity that may even grow linearly with the number of antennas, but they are not designed for achieving a transmit diversity gain for combating the effects of fading. By contrast, the family of Space-Time Block Codes (STBCs) offers a benefical transmit diversity gain, but the STBCs cannot achieve the full MIMO capacity. In order to circumvent this problem, the Linear Dispersion Code (LDC) concept may be introduced to resolve this tradeoff, where a total number of N_Q modulated MPSK/QAM symbols are dispersed across both the N_T-element spatial domain and the N_P-element time domain of the transmission matrix. As a result, the LDC may attain both the full MIMO capacity and the full transmit diversity gain, provided that the parameters satisfy $N_Q \geq N_T N_P$. Nonetheless, since the STBC's orthogonality requirements are dropped by the LDC design, the LDC receiver has to employ the V-BLAST detectors in order to tackle the Inter-Antenna Interference (IAI). Hence a tradeoff between the performance attained and the complexity imposed is encountered, which explicitly manifests itself in the context of V-BLAST receiver design. More explicitly, on the one hand, it is well known that the ML detector and the SD are capable of achieving the best possible V-BLAST performance in uncoded systems, but their detection complexity may be potentially excessive, when employing a large number of Transmit Antennas (TAs). The optimum MAP V-BLAST detection complexity may become especially unaffordable, when the MIMO detector is invoked several times in the context of turbo detection in coded systems. On the other hand, linear V-BLAST receivers such as the classic MMSE receiver may be invoked in order to separate the superimposed parallel data streams. However, the residual IAI persisting after the linear interference-suppression filter

may still severely degrade the MIMO system's performance. Against this background, the Spatial Modulation (SM) concept may be introduced. Our goal is to ensure that the optimal ML MIMO detection performance may be achieved for SM at a substantially reduced complexity. More explicitly, the SM transmitter activates a single one out of N_T TAs in order to transmit a single modulated MPSK/QAM symbol. As a result, the SM receiver may aim for detecting the TA activation index and the modulated symbol index separately at a reduced complexity. Moreover, the concept of Space-Time Shift Keying (STSK) once again achieves a beneficial diversity gain, where a single one out of N_Q dispersion matrices is activated for dispersing a single modulated MPSK/QAM symbol. The STSK receiver may employ the low-complexity SM detectors in order to recover both the activated dispersion matrix index and the modulated symbol index. However, completely independently detecting the TA activation index and the modulated MPSK/QAM symbol imposes a performance loss on the SM receiver. This is because the potentially erroneous decisions concerning the TA activation index may mislead the MPSK/QAM demodulator into detecting the wrong symbol. In order to mitigate this problem, in this treatise, we have proposed reduced-complexity algorithms conceived both for hard-decision-aided SM detection and for soft-decision-aided SM detection, where the optimal SM performance is retained by taking into account the correlation between the TA activation index and the modulated MPSK/QAM symbol index. A range of other optimal and suboptimal SM detectors characterized in the literature are also summarized for the sake of comparison.

Declaration of Authorship

I, **Chao Xu**, declare that the thesis entitled **Reduced-Complexity Communications System Design** and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Parts of this work have been published.

Signed: ..... Date: .....

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List of Publications

Journals:

1. **C. Xu**, S. X. Ng and L. Hanzo, ”Near-Capacity Irregular Convolutional Coded Cooperative Differential Linear Dispersion Codes Using Multiple-Symbol Differential Detection”, IEEE Signal Processing Letters, vol.18, no.3, pp.173-176, March 2011.

2. **C. Xu**, S. Sugiura, S. X. Ng and L. Hanzo, ”Reduced-Complexity Noncoherently Detected Differential Space-Time Shift Keying”, IEEE Signal Processing Letters, vol.18, no.3, pp.153-156, March 2011.

3. H. A. Ngo, **C. Xu**, S. Sugiura and L. Hanzo, ”Space-Time-Frequency Shift Keying for Dispersive Channels”, IEEE Signal Processing Letters, vol.18, no.3, pp.177-180, March 2011.

4. D. Yang, **C. Xu**, L. L. Yang and L. Hanzo, ”Transmit-Diversity-Assisted Space-Shift Keying for Colocated and Distributed/Cooperative MIMO Elements”, IEEE Transactions on Vehicular Technology, vol.60, no.6, pp.2864-2869, July 2011.

5. **C. Xu**, L. Wang, S. X. Ng and L. Hanzo, ”Multiple-Symbol Differential Sphere Detection Aided Differential Space-Time Block Codes Using QAM Constellations”, IEEE Signal Processing Letters, vol.18, no.9, pp.497-500, Sept. 2011.

6. **C. Xu**, S. Sugiura, S. X. Ng and L. Hanzo, ”Reduced-Complexity Soft-Decision Aided Space-Time Shift Keying”, IEEE Signal Processing Letters vol.18, no.10, pp.547-550, October 2011.

7. S. Sugiura, **C. Xu**, S. X. Ng and L. Hanzo, ”Reduced-Complexity Coherent Versus Non-Coherent QAM-Aided Space-Time Shift Keying”, IEEE Transactions on Communications, vol.59, no.11, pp.3090-3101, November 2011.

8. H. V. Nguyen, **C. Xu**, S. X. Ng and L. Hanzo, ”Non-Coherent Near-Capacity Network Coding for Cooperative Multi-User Communications”, IEEE Transactions on Communications, vol.60, no.10, pp.3059-3070, October 2012.

9. S. Sugiura, **C. Xu**, S. X. Ng and L. Hanzo, ”Reduced-Complexity Iterative-Detection-Aided Generalized Space-Time Shift Keying”, IEEE Transactions on Vehicular Technology, vol.61, no.8, pp.3656-3664, October 2012.

10. **C. Xu**, S. Sugiura, S. X. Ng and L. Hanzo, ”Spatial Modulation and Space-Time Shift Keying: Optimal Performance at a Reduced Detection Complexity”, IEEE Transactions on Communications, vol.61, no.1, pp.206-216, January 2013.

11. **C. Xu**, D. Liang, S. Sugiura, S. X. Ng and L. Hanzo, ”Reduced-Complexity Approx-Log-MAP and Max-Log-MAP Soft PSK/QAM Detection Algorithms”, IEEE Transactions on Communications, vol.61, no.4, pp.1415-1425, April 2013.

12. **C. Xu**, D. Liang, S. X. Ng and L. Hanzo, "Reduced-Complexity Noncoherent Soft-Decision-Aided DAPSK Dispensing With Channel Estimation", IEEE Transactions on Vehicular Technology, vol.62, no.6, pp.2633-2643, July 2013.

13. L. Wang, L. Li, **C. Xu**, D. Liang, S. X. Ng and L. Hanzo, "Multiple-Symbol Joint Signal Processing for Differentially Encoded Single- and Multi-Carrier Communications: Principles, Designs and Applications", IEEE Communications Surveys & Tutorial, vol.16, no.2, pp.689-712, Second Quarter 2014

14. H. V. Nguyen, **C. Xu**, S. X. Ng and L. Hanzo, "Near-Capacity Wireless System Design", *submitted to* IEEE Communications Surveys & Tutorial.

15. **C. Xu**, X. Zuo, S. X. Ng, R. G. Maunder and L. Hanzo, "Reduced-Complexity Soft-Decision Multiple-Symbol Differential Sphere Detection", *submitted to* IEEE Transactions on Communications.

Conferences:

1. **C. Xu**, S. Sugiura, S. X. Ng and L. Hanzo, "Reduced-complexity noncoherently detected Differential Space-Time Shift Keying", in Proceedings of IEEE Wireless Communications and Networking Conference (WCNC'11), pp.1505-1510, Cancun, Mexico, 28-31 March 2011.

2. **C. Xu**, S. X. Ng and L. Hanzo, "Near-Capacity Irregular Convolutional Coded Cooperative Differential Linear Dispersion Codes Using Multiple-Symbol Differential Decoding Aided Non-Coherent Detection", in Proceedings of IEEE International Conference on Communications (ICC'11), Kyoto, Japan, 5-9 June 2011.

3. H. V. Nguyen, **C. Xu**, S. X. Ng, J. L. Rebelatto, Y. Li and L. Hanzo, "Near-Capacity Non-Coherent Network-Coding Aided Scheme for Cooperative Multi-User Communications," in Proceedings of IEEE Vehicular Technology Conference (VTC'11 Fall), San Francisco, USA, 5-8 September 2011.

4. **C. Xu**, C. Liu, S. X. Ng and L. Hanzo, "Multiple-Symbol Differential Sphere Decoding Aided Amplify-and-Forward Differential Space-Time Modulation", in Proceedings of IEEE Vehicular Technology Conference (VTC'11 Fall), San Francisco, USA, 5-8 September 2011.

5. **C. Xu**, E. Ternon, S. Sugiura, S. X. Ng and L. Hanzo, "Multiple-Symbol Differential Sphere Decoding Aided Cooperative Differential Space-Time Spreading for the Asynchronous CDMA Uplink", in Proceedings of IEEE Global Communications Conference (GLOBECOM'11), Houston, USA, 5-9 December 2011.

6. S. Sugiura, **C. Xu** and L. Hanzo, "Reduced-Complexity QAM-Aided Space-Time Shift Keying", in Proceedings of IEEE Global Communications Conference (GLOBECOM 2011), Houston, USA, 5-9 December 2011.

7. **C. Xu**, D. Liang, S. Sugiura, S. X. Ng and L. Hanzo, "Reduced-complexity Soft STBC detection", in Proceedings of IEEE Global Communications Conference (GLOBECOM'12), pp.4217-4221, Anaheim, USA, 3-7 December 2012

8. **C. Xu**, D. Liang, S. Sugiura, S. X. Ng and L. Hanzo, "Reduced-Complexity Soft-Decision Aided PSK Detection", in Proceedings of IEEE Vehicular Technology Conference (VTC'12 Fall), Qubec City, Canada, September 2012

9. P. Zhang, S. Chen, **C. Xu**, J. Jiang, F. Jin and L. Hanzo, "Joint Transmit and Receive Antenna Selection Aided Differential Space-Time Shift Keying Systems", *submitted to* IEEE Global Communications Conference (GLOBECOM'15), San Deigo, 6-10 December 2015.

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