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Report on Knowledge Gaps, Action Plan, and Partners' Skills

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Table of Contents

1 Document Control

1.1 Abstract

This document identifies knowledge gaps in the area of signal processing for wireless networks. The gaps so identified represent fundamental obstacles which must be overcome to further advance the technological know-how in signal processing for wireless communications, if technology is to keep up with the increasing demand for wireless communications and services. Particular attention is given to advanced coding, modulation, mobility, and multiple access technologies, stressing practical limitations of today's technology, and highlighting emerging techniques and analysis tools necessary to advance Europe's command in this sector. The roles of the different partners comprising Newcom in overcoming these knowledge gaps is detailed for each knowledge gap so identified.

1.2 Keywords

Signal processing for wireless newtorks; Error correction coding; Signal design; OFDM systems; MIMO systems; Large-scale systems; Wideband scalability; Multi-bit coding; Turbo receivers; advanced signal processing algorithms; Multiuser coding; Space-time coding; User mobility.

2 Management Overview

2.1 Executive Summary

This document represents the first deliverable for Department 1: "Signal Processing at Large for Wireless Networks". The critical knowledge gaps that the network is to address and, with sufficient effort, fill, are identified in a synthetic manner. For the benefit of the non-specialist, mathematical equations have been avoided, even though the research work necessary to overcome the identified gaps will contain a strong mathematical component. The document also develops an action plan for filling the identified knowledge gaps. This action plan identifies which partners will contribute as a function of the identified knowledge gap, which approach or solution each contributing partner plans to investigate or develop, and forms a basis for ongoing and future collaborations among the partners with respect to the scientific research component of Department 1 within Newcom. Unless stated otherwise, the anticipated results specified in the action plan all aim for delivery at $T_0 + 18$ months.

2.2 Scope Statement

The document scope encompasses the scientific problems that the collaborative research efforts within Department 1 of Newcom aim to address.

3 Introduction

NEWCOM provides a privileged opportunity to coordinate research efforts towards tackling the shortcomings exposed by present-day knowledge gaps in the areas of wireless networking, whose solutions can only provide a bridge to introducing next-generation techniques consolidating reliability and high performance measures. The following sections serve to identify the principal knowledge gaps in signal processing for wireless networks, that present obstacles to further growth in the wireless communications sector. Subsequent sections expose knowledge gaps and our avenues for bridging them in the subdomains of (i) Error Correction Coding for Moderate Block Lengths; (ii) Signal Design for OFDM and MIMO Systems; (iii) Coding Design for OFDM and MIMO Systems; (iv) Large-Scale Multi-User and Multi-Antenna System Analysis; (v) Wideband System Scalability; (vi) Multi-bit per Hertz coding; (vii) Joint (Turbo) Receiver Optimization; (viii) Advanced Signal Processing Algorithms for Wireless Communications; (ix) Multiuser Space-Time Coding; and (x) User Mobility Tracking and Handoff Algorithms.

3.1 Glossary

CDMA:

Code Division Multiple Access, a means of allowing multiple users to share a communication channel by assigning each a signature code.

Channel capacity:

The maximum amount of information (in entropy terms) that can be sent over a communication channel per symbol or per unit time.

Cramér-Rao bound:

The theroretical minimum estimation variance that an unbiased estimator can achieve.

CSI:

Channel State Information, whose knowledge greatly assists in alleviating channel-induced imperfections in a received signal.

Cyclic prefix:

A prefix derived from the tail symbols of a packet. When such a prefixed packet is sent over a multipath channel, the resulting intersymbol interference takes the form of a cyclic convolution, which can be undone using fast Fourier transform techniques.

EM algorithm:

The Expectation-Maximization algorithm, in which successive steps perform expectation and then maximization steps, until convergence is observed.

EXIT chart:

EXtrinsic Information Transfer chart: a graphical means of studying convergence in iterative decoding algorithms, by examing the exchange of extrinsic information values between the constituent decoders.

FFT:

Fast Fourier Transform.

Galois field:

A finite field (in the formal mathematical sense) of integers modulo a prime p, offering the mathematical basis for studying the composition and coding of finite aphabets used in communications.

IFFT:

Inverse Fast Fourier Transform.

LDPC codes:

Low Density Parity Check codes, designed using sparse parity-check matrices. Proposed in 1963, the potential of such codes to approach the Shannon limit was not fully appreciated until the late 1990s.

MC-CDMA:

Multiple Carrier Code Division Multiple Access, an extension to CDMA is which multiple carriers are employed.

MIMO:

Multiple-Input-Multiple-Output, here referring to systems employing multple transmit and receive antennas. The channel capacity of such systems can be shown to grow linearly with the number of transmit or receive antennas, whichever is smaller.

MUD:

Multi-User Detection, a family of techniques which aim to optimally separate or extract multiple users sharing a communication channel.

OFDM:

Orthogonal Frequency Division Multiplexing, a method of splitting a communication channel across mutually orthogonal carriers, offering in its simplest form greater robustness against frequency-selective propagation conditions.

PAR:

Peak-to Average power Ratio, a critical performance measure in energy-efficient communication systems.

Pseudo-codeword:

A convergent point of a decoding algorithm which is not in fact a code word in the encoder's dictionary.

PSK:

Phase-Shift Keying, a modulation method in which different symbols are distinguished by changes in the carrier phase.

QAM:

Quadrature Amplitude Modulation, a technique for sending two symbols simultaneously by using the in-phase and quadrature components of the carrier frequency.

Shannon limit:

> The limiting signal-to-noise ratio for which the channel capacity matches the source entropy. For signal-to-noise ratios higher than this limit, error-free communication is theoretically possible; for signal-to-noise ratios lower than this limit, a theoretical lower bound on the probability of error can be shown irrespective of any error correction coding employed.

Trellis codes:

> Also called convolutional codes, their state transition graphs resemble a garden trellis; hence the name. Can be decoded efficiently using variants on the Viterbi or forward-backward algorithms.

Turbo codes:

> Also called concatenated codes, linking two or more codes together, and typically decoded using iterative message passing algorithms. These were the first practical codes offering reliable performance for signal-to-noise ratios approach the Shannon limit.

UWB:

> Ultra Wide Band, referring to a class of communication systems in which the bandwidth used is at least 25% the value of the mean frequency.

Water-filling:

> A means of sharing available channel capacity among multiple users, in which the resources allocated depend on the user's signal-to-noise ratio. The graphical representation resembles water finding a common level in a basin having an uneven floor; hence the name.

3.2 Revision History

- Version 1.1 (30 November 2004) — following review by the Advisory Board.
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- Version 1.0 (18 October 2004).
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  Initial document (Newcom; edited by P. Regalia).

4 Knowledge Gaps for Signal Processing at Large in Wireless Networks

The past decade has witnessed major advances in reliable communications, having a direct impact on the volume and quality of services offered in all wireless systems. Key to these advances are the signal processing subsystems on which wireless communications are built. Despite notable recent gains in coding theory, multi-access techniques, algorithm design, and processing efficiency, the ever increasing demand for higher data rates pushes current generation designs to their practical limits. To ensure that future systems will not be confined to permanent saturation, major co-operative research efforts into the fundamental capabilities and limitations of wireless systems must be pursued, addressing the present knowledge gaps in a number of arenas: information-theoretic capacity limits in time-varying multi-user channels, short packet code design for two-way communications, optimal resource allocation strategies under quality of service constraints, and increased mobility requirements, to name just a few. Although the basic signal processing techniques exploited in wireless systems have become increasingly mature and specialised over the past few decades, recent trends indicate that the joint optimisation of the various signal processing subsystems is a necessary ingredient in solutions that are to meet future demands in wireless communications.

Newcom provides a privileged opportunity to co-ordinate research efforts towards tackling the shortcomings exposed by today's knowledge gaps, whose solutions can only provide a bridge to introducing next-generation techniques consolidating reliability and high performance measures. The following sections serve to identify the principal knowledge gaps that present obstacles to further growth in the wireless communications sector.

4.1 Error Correction Coding for Moderate Block Lengths

Present-generation high-performance codes, including turbo codes and low density parity check codes, work extremely well for large block lengths, approaching ever closely the theoretical Shannon capacity as the block length increases. For short to moderate block lengths (i.e., up to about 5000 per block) on the other hand, there appears considerable room for improvement. Since two-way communication systems work with fairly short packets and/or tight delay constraints, better short codes and decoding methods would have a substantial impact on interactive communication systems.

Key knowledge gaps here concern (i) theoretical capacity limits and error floors that incorporate short block lengths; and (ii) code classes which approach these capacity limits.

Capacity limits versus block length can be obtained analytically (e.g., [24]) and nearly approached using certain classes of turbo codes. Equally important, however, is to gauge the error floors of practically encoded systems since, for robustness reasons, most practical systems will not be operating in the waterfall region.

The best known codes both for very short block lengths (trellis codes) and for large block lengths (turbo codes, low density parity check codes, etc.) are naturally described by factor graphs, and are decoded by message passing algorithms (usually the sum-product or the max-product algorithm). Therefore, the proposed research is primarily targeted towards codes that are suitable for decoding by message passing. It seems likely that the graphical descriptions of such codes will lie somehow "in-between" trellises (whose codes are cycle-free, but have many states) and the graphs of low-density codes (which have lots of cycles and no state variables). An example of such "in-between" graphs are tail-biting trellises (with a single cycle), which are well-known to provide excellent performance for a limited range of block lengths.

Concerning the message passing algorithms in particular, an unresolved issue is how to approach maximum likelihood decoding with the least effort: Simple message passing suffers from the problem of convergence to non-codewords (pseudocodewords). The occurrence of such pseudocodewords is in many cases the major cause of errors, and sets the error floor. On the other hand, there are enhancements to the basic algorithm that improve performance, but so far there is still a gap until maximum likelihood decoding is achieved.

At present, the set of candidate "high performance" codes is rather vast: in addition to turbo codes and low-density parity check codes, one may cite repeat-accumulate codes, woven codes, Tanner codes, complementary Golay codes, Reed-Muller codes, and so forth. Clearly a set of theoretical tools which could rapidly assess the cost/performance trade-offs of the multitude of choices would be of great benefit to design engineers, from initial design phases to end prototyping. This theory should aim to merge existing, but disparate descriptions, deriving notably from graph theory, density evolution, and EXIT charts, and accommodate a wide variety of channels, from the simplest Gaussian channels, binary erasure channels, and binary symmetric channels, to more complicated multi-input–multi-output channels containing memory and nonlinearities. The sparsity of such analysis tools constitutes an additional knowledge gap, whose solution would also impact MIMO system design as well as synchronisation and equalisation tasks.

With respect to the overall focus of NEWCOM, investigations on the area of moderate length codes should also take into account constraints on decoding complexity, decoding delay, and the trade-off between encoding/decoding processing. The impact of these practical constraints on coded modulation schemes of short length and with high spectral efficiency should also be addressed.

Action Plan

- ISMB (01):
  - **Pseudo-codeword analysis:**
    Analysis of the effect of pseudo-codewords on the message passing decoder; development of decoders able to fight pseudo-codewords and/or development of design algorithms of codes free from low-weight pseudo-codewords.
- Intracom (04):
  - **Adaptive modulated convolutional codes:**
    Exploitation of the performance of adaptive modulated convolutional codes and iteratively decoded codes to examine which affords best performance in the short block length case. Different channel models will be considered in order to cover a wide range of applications. Investigation of improving the performance of convolutional turbo codes (e.g., Adaptive convolutional turbo codes).
- Technion (05):
  - **Analytic bounding for linear codes:**
    Research into the issue of analytical bounding techniques for linear codes, focusing on information based combining on the one hand as well as general analytical bounds which apply also to maximum likelihood detection on the other. The research effort focused on information combining will be carried out by Ilan Sutskover and Prof. Shlomo Shamai, while that exploring general analytical bound will be based on the work by Dr. Igal Sason and Prof. Shlomo Shamai. Potential NEWCOM partners on this study, with whom contacts have been established, include Prof. Sergio Benedetto of Politechnico di Torino, Italy and Prof. Johannes Huber of University Erlangen-Nuremberg, Germany.
- UPF (10):
  - **Rate-compatible concatenated codes:**
    Analysis and design of rate-compatible Serial Concatenated Convolutional Codes (SCCC) for short to moderate lengths. The aim is to provide a formal analysis of a new class of

SCCC where the inner encoder can be punctured beyond the unitary rate and address suitable design criteria for this particular code structure. Further work includes collaborative research with Guido Montorsi at the Politecnico di Torino (also involved in NEWCOM) and Francesca Vatta at the Università di Trieste (not involved in NEWCOM), on the analysis of convergence properties of turbo codes. The purpose is to analytically predict the convergence properties of Turbo Codes (and related codes as LDPC codes, etc.) and to derive optimal criteria for the design of constituent codes for Turbo Codes with good properties in the convergence region.

- GET (17):
  - **Non-binary concatenated codes:**
    Performance of current iteratively decoded codes (CTC, BTC and LDPC) exhibit significant degradation for short blocks with respect to channel capacity. An attractive solution to this problem might come from the use of non-binary codes which have not been intensively investigated up to now. We propose to investigate iteratively decoded non-binary codes for short block applications both from the theoretical and practical point of view. Different channel models will be considered (AWGN, Rayleigh, BSC, BEC) in order to cover a wide range of applications.
- CNRS (19):
  - **Non-binary low-density parity check (LDPC) codes:**
    We will investigate the error correction capability of non-binary LDPC codes built in very high order Galois fields, up to GF(256). These types of LDPC codes have shown very good empirical performance for short block lengths (less than 500 information bits). While the non-binary LDPC codes have to be regular to reach good performance, the optimisation of these codes is focused on the choice of the non-binary values in the parity matrix and constructions of matrices that minimise the number of small cycles.
- France Telecom (21):
  - **Tanner Tail-Biting (TTB) binary codes with low-complexity 2-state and 4-state trellis and fair comparison with LDPC and Turbo Codes:**
    The goal of this approach is to design error-correcting codes with lower complexity decoding than present competitive LDPC and Turbo Codes. Tanner Tail-Biting (TTB) codes generalise LDPC and Turbo codes and, due to their structure, may be considered as hybrid between LDPC and Turbo codes. We address the problem of optimising error-correcting performance with a low error-floor, using low-complexity 2-state and 4-states trellises. In order to minimise the error-floor, it is necessary to design codes with high minimum distances, and if possible belonging to an asymptotically good family ($d/n \rightarrow$ constant > 0 when $n \rightarrow \infty$). We address also the problem of accelerating convergence to better a posteriori probability estimates by new soft-decoding algorithms belonging to the class of alternating minimisation algorithms. In addition, to make fair comparisons with LDPC and Turbo codes, we shall study EXIT charts as a tool to optimise capacity erasure corrections on erasure channels and error correction on Gaussian channels.

- LNT-TUM (28) + UoE (53):
  - **Concatenation of Convolutional Codes with Different Encoder Memories:**
    Investigation of a serial concatenation of convolutional codes with different encoder memories for moderate-to-short block lengths; iterative decoding by the turbo principle. Use of a low-complexity suboptimal decoder for the code with large memory. Investigation of the quality of the *L*-values shared within the iterations. Use of quantisation schemes for the *L*-values to reduce memory and complexity requirements.
- CNIT (32):
  - **Error floor and pseudo-codewords for LDPC codes:**
    Design of well-performing short and moderate length Low-Density Parity-Check Codes, satisfying the requirements of wireless networks. Contributions involve the estimation of the error floor due to both low-weight codewords and low-weight pseudocodewords, the performance evaluation through simulation of new coding schemes/decoding algorithms (e.g., variations to the message passing decoder), and the search for efficient encoding algorithms for LDPC codes.
- AAU (41):
  - **Analytic EXIT bounds:**
    Development of analytical methods to compute and bound EXIT functions for linear codes in order to analyse the convergence behaviour of iterative decoders. The recently introduced concept of bounding the combination of mutual information values [48] lead to bounds on information transfer functions for repetition codes, single parity-check codes, and applications to LDPC codes [78], [47]. The investigations focus on further generalisations and applications. The research effort will be carried out by Ingmar Land and Prof. Bernard Fleury. Potential NEWCOM partners include Prof. Johannes Huber of University of Erlangen-Nürnberg, Germany (building on earlier collaborations) and Prof. Shlomo Shamai of Technion, Israel.
- LU (45):
  - **Efficient decoding of block codes of short and moderate lengths:**
    We will investigate decoding of block codes of short and moderate lengths using BEAST (Bidirectional Efficient Algorithm for Searching Trees) and its variants. Recently we derived an upper bound on the asymptotic decoding complexity for BEAST that for our ensemble of double zero-tail terminated (DZT) convolutional codes is better than the best previously known bound for ML decoding at high rates. The research will be carried out by Rolf Johannesson and his student Maja Lončar in collaboration with Irina Bocharova and Boris Kudryashov from St. Petersburg.
- UoB (49):
  - **Rate-compatible turbo and LDPC codes:**
    Investigation of rate compatible turbo codes of moderate lengths. Investigate the effect of pseudocodewords, especially in LDPC codes, and decoding algorithms that are not or less affected by pseudo-codewords, similar to the work carried out at ISMB (01).

4.2 Signal Design for OFDM and MIMO Systems

The great flexibility of OFDM explains its increasing deployment in recent years. In particular, in combination with multi-antenna (or MIMO) approaches with their increased theoretical capacity, OFDM is very attractive. The increasing demand for data rate and number of users exposes, however, important knowledge gaps: (i) workable multiframe code allocation to accommodate advanced space-time codes (present systems use single-frame codes, which are too short); (ii) multi-user capacity limits over time-varying multipath channels, be they multiple-access channels or broadcast channels, and the signal/coding structure needed to achieve them (see also Section 4.9); (iii) peak-to-average power ratio (PAR) optimisation adapted to a dynamically variable numbers of users; and (iv) design of appropriate pulse shapes achieving high spectral efficiency.

Concerning the third knowledge gap, the ratio of the peak power to the average power of the transmitted signal is still hard to control without sacrificing data rate. And touching on the second knowledge gap, the signal-to-noise ratio in adjacent frequency slots is correlated; although this is a minor problem for time-invariant channels, especially when coding across many OFDM frames is allowed, it is not clear for nonstationary channels how to construct good codes and good decoding algorithms. This, in turn, confronts the first knowledge gap, namely that codes for OFDM are often required to cover only one OFDM frame, which is typically too short for turbo codes or low-density parity check codes to show their full power.

4.2.1 Peak-to-Average Power Ratio

A critical parameter in OFDM systems is the peak-to-average power ratio. A high peak-to-average power ratio results in clipping distortion caused by nonlinear power amplifiers and during signal processing (e.g., in FFT/IFFT calculations) due to limited wordlength. Tests show that the bit error rate degradation in OFDM transmission induced by nonlinear distortion may not be the key factor characterising the overall system performance. Indeed, in addition to bit error rate performance degradation, clipping causes energy to spill into adjacent channels, induces intermodulation effects on the subcarriers, out-of-band power radiation and warps signal constellations in each subchannel, which collectively constitute more serious problems. A high peak-to-average power ratio also translates into high precision requirements for digital-to-analog (D/A) converters, adding thus to system costs. For a given transmitter power level, setting the maximum level of the D/A converter too high results in severe quantisation noise, while setting it too low induces excessive clipping distortion.

A number of methods for peak-to-average power reduction in OFDM systems have been elaborated. Most of them involve various combinations of coding, windowing, and reference signal subtraction, in addition to some complicated signal manipulations, which in turn often require transmitting some overhead information. Suitable codes favouring small peak-to-average power ratios include Golay codes and generalised Reed-Muller codes. They may only be applied, however, in M-PSK OFDM systems, thus limiting their applicability. The remaining methods mentioned above can sacrifice data rate when additional side information has to be transmitted, or transmission performance when peaks are removed from a transmitted signal without restoring them at the receiver.

Filling this knowledge gap entails finding the optimum compromise between the overhead induced by side information and the allowable deterioration in performance. For example, removing a few of the strongest peaks from an OFDM signal, and thus limiting the amount of side information, can improve markedly the behaviour of the remaining performance factors. Another technique to compensate for high peak-to-average power ratios exploits predistortion in the nonlinear power amplifier, aiming for linearisation. Although many examples of the linearisation methods are found in the literature, they depend on the applied modulation. An additional knowledge gap in this direction concerns universal linearisation methods which do not depend on the digital modulation scheme. Filling this latter knowledge gap would have great impact in efficient reconfigurable radio design, which would have to accommodate a wide variety of modulation schemes.

Action Plan

- CTTC (9):
  - **Spreading code families**:
    Investigate appropriate (spreading) code families for frame synchronisation and multi-user detection in a MC-CDMA system, with special emphasis on the uplink transmission mode. Methods for reducing the peak-to-average ratio will be analysed and compared.
- CNRS (19):
  - **Linear periodically time-varying filters**:
    Investigation of PAR reduction techniques based on Linear Periodic Time Varying filters (LPTV). The class of suited LPTV filters for such PAR reduction is the lossless LPTV filter class. These LPTV are derived from Maximally Decimated Filter Banks relying on lossless matrices [11].
  - **Predistortion techniques:**
    Investigation of predistorsion methods for non-linear amplifiers used with high PAPR signals like OFDM. Predistorsion is realised in base-band with Neural Networks (MLP based architectures) and adaptation is realised using pilot symbols [1], [79]. Predistorsion can be fixed or adaptive if non stationary amplifiers are used.
- UEN (30):
  - **Sphere decoding for PAR reduction:**
    Design and investigation of PAR reduction schemes based on the application of a sphere decoder and on lattice-reduction-aided precoding principles [90] for arbitrary signal constellations and FFT sizes. A suited decoding metric has to be designed, and the aim is the development of low-complexity versions similar to selected mapping and partial transmit sequences techniques [57].
- PUT (36):
  - **Computationally efficient PAPR reduction:**
    Efficient methods to reduce high peak-to-average power ratio in OFDM and multicarrier CDMA systems. Particular stress will be put on low computational complexity of the proposed methods, minimisation of transmission overhead caused by side information, as well as on noticeable system performance improvement.
- NTNU (48):
  - **Analog-to-digital conversion and FFTs:**
    Investigation of the influence of PAR on required complexity/cost of A/D converters and FFT processing in OFDM receivers.

4.2.2 Channel State Information

Signal and coding design for MIMO systems has traditionally concentrated on two extreme cases regarding the degree of channel state information at the transmitter: perfect channel state information, for which multi-beamforming strategies are optimal, and unavailable channel state information, for which space-time codes have been proposed. Sophisticated space-time coding schemes aiming to exploit all available channel capacity are quite sensitive to channel state information errors, and the promised performance levels are met only when perfect channel state information is available, due to the need for joint decoding and demodulation at the receiver. In some schemes such joint channel estimation and decoding can present prohibitive complexity, leading in some cases to the channel estimation part being relegated to a separate acquisition phase. A key knowledge gap concerns how to best exploit a space-time code for improving the accuracy of channel state information, while retaining a reasonable complexity. Moreover, the problem of designing efficient estimation strategies that capitalise on the knowledge of the propagation features must be addressed.

In general, partial channel state information situations have been rarely addressed in the literature, and the relationship between the quality and degree of channel state information and the associated capacity-achieving architecture requires further study. Some initial theoretical and algorithmic results have been presented in [77, 42], although this still this presents a paramount knowledge gap. Clearly, scalable signal processing/coding designs that are to adapt themselves to the degree and quality of the available channel state information will prove vital to deducing optimum choices for these situations. This requires close collective collaboration among partners with signal processing and information theory backgrounds.

In time-variant multiple-access MIMO channels the exploitation of the propagation characteristics become even more important. Channel estimation methods like the Kalman [44] or Wiener filter [71] assume the detailed knowledge of second order statistics of the time-variant channel (see also Section 1.9). The same is true for subspace methods based on the Karhunen-Loève transform [72, 74]. Consistent estimators for these statistics of a multi-access MIMO channel are not available because the number of channel observations is rather limited by the spatio-temporal stationarity of the channel. It has been shown [87] that the spatial stationarity of the channel is below 100 wavelengths. Measurements at 5.2 GHz have also shown that the Jakes model, although frequently used for analysis and simulations, is a rather crude idealisation of real scattering environments [97]. These shortcomings collectively justify the need for new improved estimators for time-varying radio channels.

In addition, it is a fundamental fact that the Doppler spectrum is bandlimited by the maximum velocity of mobile users. At a first glance, the Fourier basis expansion (i.e., a truncated discrete Fourier transform) appears to be the method of choice for time-variant channel estimation defining a channel subspace [70]. The Fourier basis expansion, however, suffers from a high estimation bias due to spectral leakage and Gibbs phenomenon. Thus, it is in practice observed that the channel subspace is not accurately spanned by a truncated Fourier basis [95]. Noting that the transmitted data blocks are of finite duration, it seems reasonable to use results from the theory of bandlimited and time-concentrated sequences. In this context, it has been shown that discrete prolate spheroidal sequences span the channel subspace for time-variant channel estimation [95] per subcarrier in an OFDM based system. This subspace representation is termed the Slepian basis expansion. A dual situation exists in the frequency domain [25], so that a modified Slepian basis expansion can be applied for exploiting the correlation between the individual subcarriers [38].

Going back to the MIMO scenario, it should be pointed out that a straightforward application of time-varying SISO estimators to all elements of the MIMO matrix is inefficient. A much better approach would be to estimate the relevant MIMO channel subspaces instead. One notable example is the Krylov subspace which is especially important for multi-stage Wiener filters. The construction of estimators for time-varying multiple-access MIMO channels which take advantage out of these fundamental time limited and bandlimited properties prove to be an open question of high practical relevance to future MIMO communication systems.

Action Plan

- UPC (8):
  - **Robust techniques for imperfect channel state information:**
    Development of robust techniques and algorithms for exploitation of imperfect channel state information in MIMO systems. Analysis of different sources of imperfections in the channel estimate, such as Gaussian noise and quantisation errors, and the optimum strategies to cope with these imperfections. Theoretical development of algorithms based on robust designs using the Bayesian (statistical) and the "maximin" (best worst case) approaches.
  - **Improved space-time coding:**
    Techniques for improving the performance of classical space-time coding techniques when limited channel state information is available at the transmitter, such as the gains of the channel coefficients, and the phases of the channel coefficients, among other information. Analysis of antenna selection techniques based on limited channel state information.
  - **High spectral efficiency in the presence of feedback:**
    High spectral efficiency wireless systems where the design of the feedback channel (TDD or FDD) is taken into account in the overall multi-user system performance. Uncoded analogue linear modulation is an effective way to transfer CSI from autonomous terminals to a base station in FDD system. For instance, in MIMO systems, the MIMO effect benefits CSI transfer in the same way that it benefits the transmission of data. The aim is to design wireless systems for multiple message transmission based either on FDD or on TDD schemes.
- CTTC (9):
  - **Optimal MIMO architectures:**
    Analysis and development of optimal MIMO architectures for situations with partial channel state information at the transmitter. Design of scalable signal processing MIMO precoding schemes and evaluation of the robustness (in terms of achievable rates loss) of such systems to the variations of the quality of the available channel state information.
- CNRS (19) + VUT (24):
  - **Channel prediction for channel state information:**
    Investigation of the viability of channel prediction as a means to provide (partial) channel state information to link adaptation schemes at the transmitter. The aim is to utilise up-to-date channel state information by compensating round-trip delays via channel prediction.
  - **Partial channel state information:**
    The impact of using flawed channel state information at the transmitter (and/or at the receiver) on the receiver performance will be assessed. This work will be done for single-input/single output systems first and extended to MIMO systems as a second step.

- ETH (26):
  - **Information theoretic impact of partial channel knowledge:**
    We investigate the impact of varying degrees of channel knowledge on wideband multi-antenna communications from a communication- and information-theoretic perspective. Insights will be crucial for the design of future high mobility, high data rate wireless systems. In particular, conclusions with respect to the amount and the kind of training and with respect to the sensibility of certain coding schemes are sought.
- UEN (30):
  - **Noncoherent detection for OFDM/MIMO systems:**
    The extension of known non-coherent detection techniques for flat fading channels, in particular those based on the sphere decoder, to OFDM/MIMO systems is aspired. The aims are low-complexity and robust algorithms for use in broadband and high-rate communication schemes which should or have to work without explicit channel state information.
- CNIT (32):
  - **Channel estimation and system capacity:**
    Signal processing is expected to deal with the interaction of channel estimation and system capacity. Specifically, it would be relevant to evaluate the impact of imperfect CSI on the capacity for MIMO system over frequency selective channels. This analysis should be pursued by considering realistic channel models with analytically tractable algebraic structure so as to ease a thorough understanding of the channel estimation process. Expected results include the analysis of lower bounds on channel estimation error (e.g., hybrid Cramér-Rao bound for time-varying channels), a study of the sensitivity of link capacity with respect to channel characteristics (e.g., Doppler and delay spread, spatial correlation) and system parameters (e.g., length of the training sequence, number of antennas).
- FTW (34):
  - **Channel estimation from Krylov and Slepian subspaces:**
    Multi-stage Wiener filters take advantage of the structure of Krylov subspaces. Time-variant channel estimation exploits the structure of Slepian subspaces which is spanned by discrete prolate spheroidal sequences. Both concepts are closely related. We will exploit the combination of both Krylov and the Slepian subspaces for low-complexity channel estimation and data detection in time-variant MIMO systems.
- NTNU (48):
  - **Performance using pilot-aided link adaptation:**
    Further investigation of the impact of imperfect and/or outdated channel state information on the performance and design of OFDM and MIMO systems that utilise pilot-aided link adaptation (adaptive coded modulation). In a slightly more long-term perspective, similar investigation for opportunistic multi-user scheduling algorithms in such systems. Optimisation of link adaptation parameters in such systems (e.g., pilot period, pilot vs. information symbol power, switching thresholds) when taking imperfect CSI into account. Analysis and optimisation of link adaptation schemes with multiple receive antenna combining

when taking imperfect CSI into account. Analysis of trade-offs between channel estimator/predictor complexity and performance in the context of link adaptation and multi-user scheduling algorithms.

- UoSo (51):

  - **Minimum bit error rate multi-user detectors:**
  The family of minimum bit error rate (MBER) multi-user detectors (MUD) is capable of outperforming the classic minimum mean-squared error (MMSE) MUD in terms of the achievable bit error rate (BER) owing to directly minimising the BER cost function. This powerful design paradigm may also be successfully applied to multi-user OFDM systems. The underlying approach is that commencing from the MMSE solution for example, the gradient of the bit error probability (BEP) is estimated using kernel density estimation (KDE) and the MUD's weights are iteratively updated for example with the aid of the conjugate gradient algorithms for the sake of minimising the estimated BEP. The difficulty in this process is that the achievable performance would substantially depend on the specific choice of a number of algorithmic parameters, such as the algorithm's step-size. In order to circumvent the associated problems, random guided search algorithms, such as genetic algorithms, may be invoked for finding the optimum weight vectors of the MBER MUD in the context of multiple-antenna aided multi-user OFDM [33]. Initial results [3] indicate that the MBER MUD is capable of supporting more users than the number of receiver antennas available, while outperforming the MMSE MUD.

  - **Adaptive beamforming for minimum bit error rate:**
  Adaptive antenna array assisted spatial processing has shown real promise in terms of substantial capacity enhancements in wireless communications. The above-mentioned MBER principles are also applicable to employment in adaptive beamforming and utilises the antenna array elements more intelligently, than the standard minimum mean square error (MMSE) approach [13]. Consequently, MBER beamforming is capable of providing significant performance gains in terms of a reduced bit error rate over MMSE beamforming. A block-data adaptive implementation of the theoretical MBER beamforming solution was developed based on the classical Parzen window estimate of probability density function. Furthermore, a sample-by-sample adaptive implementation was also considered, and two stochastic gradient algorithms, namely the least bit error rate (LBER) and approximate LBER (ALBER) techniques were derived. However, there are a number of further open research problems to be solved in the context of rapidly fading wideband channels. Furthermore, when applying similar principles to CDMA MUD, numerous open problems arise. For example, the achievable performance depends strongly on the specific choice of spreading codes used and this deficiency has to be addressed in the context of rapidly fading channels [14, 15, 69].

- UoY (61):

  - **Iterative decoding and channel estimation techniques for MIMO systems:**
  Iterative techniques have been shown to be very effective for carrier phase recovery [96], and for MIMO channel estimation on time-invariant channels [55]. Time-variant channels, however, represent a significantly more difficult problem, upon which work is only now beginning, and which is essential in order to extend the mobility range of broadband wireless systems. B-spline models of the time variation have been investigated, and this approach

will be applied to doubly-selective MIMO channels, using both single carrier and OFDM approaches.

- **Interference cancellation for double-selective MIMO-OFDM systems:**
  On rapidly time-variant channels, OFDM systems are subject to interchannel interference due to loss of orthogonality of the sub-carriers. On doubly-selective channels using space-frequency or space-time block codes (SFBC or STBC) there is additionally interference due to loss of orthogonality in the orthogonal designs. A promising approach for overcoming this is iterative interference cancellation, which has been applied to these problems separately, but not to their combination on doubly-selective channels.
- **Differential space-time coding:**
  This approach, related versions of which were introduced by Hochwald and Sweldens [37], and by Tarokh and Jafarkhani [81] avoids the need for channel estimation. However, these codes are restricted to low rates. Higher rates could be achieved using quasi orthogonal STBCs [41], but this would lead to interference, as would in any case the effect of channel time variation. Joint iterative decoding techniques, however, provide a potential means for overcoming these effects.

4.2.3 Blind Acquisition — Channel and Data Estimation

For specific applications such as sensor networks, ad-hoc networks, short packet communications, and intelligent vehicular communication systems, it is paramount that the receiver recognise the system configuration, the channel conditions or the type of transmitted data, with the minimum possible a priori knowledge of system and channel parameters. Advanced techniques in receiver design permit blind or non-blind acquisition and estimation of various parameters, such us channel parameters and modulated data (cf. Section 4.8).

The knowledge gaps in this area include such topics as (i) optimum selection between pilot based or non-pilot based (blind) estimation for flat or frequency selective channels; (ii) data aided estimation of unknown parameters; and (iii) blind acquisition and demodulation over flat or frequency selective channels for higher modulation schemes. Also in consideration is the simultaneous estimation of data sequence and unknown channel parameters with the use of trellis structures and per-survivor-processing based algorithms.

Action Plan

- GET (17):
  - **Analytic performance bounds:**
    Derivations and analysis of lower bounds (Barankin bound, Ziv-Zakai bound) for synchronisation parameters at low SNR, and comparison with real SNR threshold observed in standard estimation algorithms.
  - **Capacity for superimposed training sequences:**
    A contribution for developing channel estimators based on superimposed training sequence and following by a fair comparison with sequential training sequence based methods in terms of capacity, estimation accuracy.

- CNRS (19):
  - **Performance of carrier frequency estimation:**
    Carrier frequency estimation in synchronisation phases will be investigated similarly to channel parameter estimation, focusing on the statistical performance of such algorithms at low SNR values. The threshold region (SNR threshold) and the corresponding lower bound will be investigated. In order to predict estimation performance relevant to real systems, it is necessary to investigate the effect of a limitation of finite observations (by a detection criterion, for example) both on theoretical bound (conditioned Cramér-Rao bounds) and analytic performance measures (mean and standard deviation).
  - **Performance of timing error estimation:**
    Timing error estimation techniques with OFDM systems can be carried out before or after the FFT demodulation, i.e., in the time or frequency domains. This study will highlight the pros and cons of the two approaches, based on simulation results and analytic performance measures.

4.2.4 Pulse Shape Design

Conventional OFDM systems use a rectangular waveform in the time domain that leads, with a sinc impulse, to poor localisation in the frequency domain. Furthermore, in a practical set-up this rectangular pulse has to be extended by a so-called “guard interval” corresponding usually either to a cyclic prefix or to zero padding which, in either case, leads to a loss of spectral efficiency. Despite various studies that have been carried out to design pulse shapes matched to different transmission channels and also allowing a maximum spectral efficiency, there are still gaps to fill in designing multicarrier modulation systems of acceptable complexity that can significantly outperform conventional OFDM systems.

This rectangular waveform can be modified by appropriate windowing. But in a standard OFDM set-up, in order to remove the resulting inter symbol interference, this leads either to the need for a post-processing equaliser [54], [52] or to the addition of an extra guard interval [64]. Another windowing technique leading to good frequency localisation consists in oversampling, thus reducing the overlap between subchannels and producing some sort of equivalent of the time guard interval in the frequency domain. This again translates into a loss in spectral efficiency. Furthermore, in the approach known as filtered multitone the resulting system is only approximately orthogonal. The orthogonality may be preserved, however, as shown for oversampled filter bank systems [36], [51]. The knowledge gap to fill in this context concerns how to design perfectly orthogonal systems with rational oversampling factors being as close as possible to 1 [65] to retain spectral efficiency.

Another way to introduce pulse shaping without loss of orthogonality is to include a time-offset when modulating each subcarrier. For instance, the Offset-QAM modulation format [7] has been used to get, in the real field, a set of orthogonal waveforms named IOTA (Isotropic Orthogonal Transform Algorithm). This method has the nice property of being nearly optimal with respect to an appropriate time-frequency localisation criterion. Moreover, it can reach maximum spectral efficiency, unlike standard OFDM using cyclic prefixes or zero padding, and can be efficiently implemented thanks to fast Fourier transform algorithms. Compared to classical OFDM, however, the pre- and post-polyphase filters lead to additional computational complexity. As shown in the filter bank implementation described in [76], though, nearly optimal results can be obtained with very short waveforms.

A theoretical analysis [46] reveals that, for transmission over time- and frequency-dispersive channels, orthogonal waveforms are no longer the best choice and that non orthogonal waveforms should be used instead. Thus biorthogonal generalisations of OFDM/Offset-QAM have already been investigated [75], [7] that are potential candidates for 4th generation mobile communication systems.

A practical knowledge gap to fill for all these pulse shaped multicarrier modulation systems concerns their capabilities in real transmission conditions over mobile radio channels. For instance, the above mentioned problem of peak-to-average power ratio has to be revisited in this context and specific solutions may be derived. To be competitive with the simple OFDM frequency domain equaliser, some progress will also be certainly necessary compared to the present state of the art in this field. Finally, if the idea of biorthogonal modulation may be attractive from a conceptual point of view for time-frequency dispersive channels, at present measurement reveal little more than the performance loss over additive white Gaussian noise channels; considerable room remains for future improvements.

Action Plan

- France Telecom (21):
  - **Short waveforms with peak-to-average power constraints:**
    Analysis and design of short waveforms taking into account the peak-to-average-power-ratio criterion for different types of multicarrier systems. Practical evaluation of these systems for transmission over mobile radio channels.
- VUT (24):
  - **Pulse shape design for OFDM/BFDM:**
    Development of pulse shape design and optimisation algorithms for OFDM/ BFDM (bi-orthogonal FDM) systems and recently introduced multipulse multicarrier systems. The goal is to study existing pulse shaping approaches with regard to ISI/ICI, PAPR, resilience to clipping, narrowband interference, and synchronisation errors. Furthermore we aim to develop advanced OFDM/BFDM pulse optimisation algorithms to achieve further performance enhancements.
- NTNU (48):
  - **O-QAM modulation:**
    Optimisation of an OFDM system using O-QAM modulation with pulse shaping. Design of pulse shapes with low bandwidth, low sensitivity to carrier frequency offset, etc.

4.3 Coding Design for OFDM and MIMO Systems

Broadband OFDM systems generally offer not only time diversity, but also frequency diversity stemming from independently fading propagation paths. In broadband MIMO systems, spatial diversity provides an additional potential benefit. Although practical experience confirms that fourth or fifth order diversity is usually sufficient in wireless communication systems, it is still of utmost importance to exploit the additionally available diversity in broadband systems: Due to delay constraints and low mobility, temporal diversity is often not available, and it is generally desirable to employ multiple transmit antennas for boosting data rate through spatial multiplexing (a.k.a. BLAST), instead of exploiting spatial diversity.

For flat-fading MIMO systems, a host of well-performing schemes have been proposed so far, most notably vertical and diagonal Bell Labs layered space-time modulation (V- and D-BLAST), space-time block codes (STBCs), space-time trellis codes (STTCs), linear dispersion codes (LDCs), and threaded algebraic space-time modulation (TAST). Moreover, the performance of these schemes has reached a mature level of understanding. Conversely, a sizeable knowledge gap surrounds space-frequency code design, where both spatial and frequency diversity are jointly exploited. Although design criteria are readily devised [80], no standard schemes have emerged so far. In particular, it would be desirable to have simple schemes that exploit a prescribed order of spatial and frequency diversity, on top of which an arbitrary outer code could be used for additional coding gain. Such a scheme would allow one to allocate the channel's degrees of freedom to multiplexing and diversity transmission modes in a flexible fashion. This should be pursued by defining a common framework under which one may classify all existing space-time coding and MIMO precoding schemes based on, e.g., diversity gain, coding gain, multiplexing gain, complexity, and robustness to channel errors. This should set the stage for design principles of space-time codes targeting a predefined signal-to-noise ratio, quality of service constraints, and system complexity.

MIMO schemes can be shown to give considerable increases in link capacity in noise limited systems. However, when a system is interference limited, it can no longer be assumed that transmit antenna diversity and/or space-time coding will offer better gains than receive antenna diversity [9]. When there are more antennas at the receiver than at the transmitter, interference suppression can be performed. As a result, for channels with high levels of interference, receive antenna diversity will offer better gains than space-time coding or transmit antenna diversity, with the latter offering higher capacities when the channel conditions are more favourable [21]. In high data rate systems such as 1xEV-DO and HSDPA, the base station transmits with full power to a single user at a time. Adaptive modulation, coding and state of the art precoding schemes are used to transmit data at a rate appropriate to the channel conditions. This allows the system to take advantage of multi-user diversity. However, for the base station to transmit at the correct rate, the transmit power must not change between the transmission of the pilot and the data transmission. Therefore if MIMO is to be used in this type of system, techniques such as water filling cannot be used. It has also been found that the comparative performance of systems using multiple antennas can depend strongly on the type of scheduling algorithm used [22]. Using multiple antennas will also tend to decrease the channel diversity, decreasing the multi-user diversity gains. Therefore, considering the interaction between scheduling methods and multiple antenna precoding techniques may produce methods which will improve the performance of high data rate systems.

Since there are more channel coefficients to be estimated for broadband MIMO-OFDM systems compared to their narrowband counterparts, accurate channel estimation will pose serious challenges in high-mobility scenarios. It is, therefore, of high relevance to devise space-frequency codes that are suited for decoding with partial or no channel knowledge at the receiver. Also, since the channel characteristics may vary widely in different scenarios, it is important to design codes that are either robust and offer close to optimum performance in differing propagation settings, or codes that are easily adaptable to the propagation environment. This can be viewed as adapting the shape of a codeword based on the shape of the transmission channel in order to approach channel capacity.

Somewhat related to the last point, the channel coefficients in a (MIMO)-OFDM system vary from subcarrier to subcarrier, although they are usually highly correlated, depending on the channel power delay profile. It may therefore be possible to develop schemes for space-frequency decoding that exploit this correlation, resulting in greatly reduced computational complexity. Manageable complexity is paramount for schemes that require matrix inversion at the receiver, such as BLAST.

Finally, an emerging theme concerns "co-operative diversity" in which multiple transmitters, possibly in an ad-hoc or peer-to-peer configuration, devise their own "macrodiversity" scheme based on available resources. Here again the uncharted territory includes capacity of the network, algorithms and codes which approach capacity, repetition and/or sharing strategies, with the added complication of a dynamic and ever-changing network configuration.

Action Plan

- NKUA/IASA (02):

  - **Global catalogue of space-time codes:**
    Space-Time Code (STC) design has been mainly based on the pioneering work presented by Tarokh *et al.* [80] where design principles were first established. Our first action will be to define a common framework under which one can fairly characterise all existing space-time coding schemes (i.e., based on diversity gain, coding gain, multiplexing gain, complexity, robustness to channel errors) and then to identify design principles targeting a pre-ordained SNR operating point, quality-of-service requirements and system complexity. During this effort the performance of all the proposed space-time coding schemes found in the literature will be examined under various channel propagation scenarios and system impairments.

  - **Adaptive codeword shaping:**
    The SNR variation across the carrier tones of a typical OFDM system depends mainly on the power delay profile of the channel and strongly affects the performance of the system. Several bit- and power-loading techniques have been proposed in order to approach the capacity of the underlying channel. In a COFDM system with bit and power loading, a code designed for an additive white Gaussian noise channel is most often used. It has been noted that the performance of such systems is strongly affected by the constellation granularity and the bit assignment algorithm (power loading is usually ignored). Our goal will be to devise new coding procedures that adapt the number of information bits per constellation symbol inside a codeword (usually one codeword has the length of an OFDM symbol). That is, we aim to adaptively give a shape to the codeword based on the shape of the transmission channel in order to approach the capacity of the channel.

- Technion (05) + Eurécom (22):

  - **Dirty paper [18] coding techniques**:
    These techniques are now very well recognised, as they play a fundamental role in approaching the capacity limits of a MIMO broadcast channel. Extensive research efforts have been directed to this technique, following the pioneering efforts by Erez, Shamai and Zamir. A new concept, namely dirty paper coding based on a superposition approach, will be developed in the first 18 months of this project, with an initial report due in October 2004. This effort is conducted in full co-operation between NEWCOM members Prof. Shlomo Shamai of Technion and Prof. Giuseppe Caire of Eurécom.

  - **Linear Precoding for fixed receivers:**
    Our main performance measure is the worst signal to interference and noise ratio (SINR) among all the subchannels in the system, rather than the standard minimum mean squared error (MMSE) criterion. This measure is more related to practical communication performance metrics as bit error rate (BER) and/or capacity. In our research we intend to explore the design for linear systems, as well as non-linear systems. In addition, we will consider the case of the design under perfect channel state information (CSI), as well as the problem of robust design under different partial CSI. This research is conducted by Ami Wiesel, Dr.

Yonina Eldar and Prof. Shlomo Shamai. Potential NEWCOM partners on this endeavour, with whom contacts have been established are: Prof. Helmut Bölcskei of ETH, and Prof. Giuseppe Caire of Eurécom.

- UPC (8):
  - **Multi-user scheduling:**
    Development of multi-user scheduling strategies that take advantage of the capacities provided by the multiple antennas at the transmitter and/or the receiver. Inclusion of fairness criteria in the scheduling algorithms. Design of multi-user robust schemes trying to incorporate recent research into robust point-to-point MIMO systems against limited channel knowledge.
- CNRS (19)
  - **Optimisation of MIMO MC-CDMA based on space-time block coding:**
    During this study, different schemes based on the combination of Orthogonal Block Codes with MC-CDMA will be considered in the first part. Then, in order to obtain higher data rates, generic Space Time Block Codes (Non Orthogonal Linear Dispersion Codes) will be considered over realistic MIMO channels. For each scheme, we will investigate the redundancy trade-off between the channel code, space-time code, and constellation in order to obtain highest throughput.
- France Telecom R&D (21):
  - **Linear precoded OFDM:**
    The aim of linear precoding, based on linear combinations between complex input symbols, is to efficiently exploit frequency and/or time diversity of the channel. This technique requires no channel state information (CSI) at the transmitter side. When applied to a MIMO scheme, with either STBC or spatial multiplexing, iterative receiver techniques can be employed to remove interference. Receiver schemes and corresponding performance results will be provided over theoretical and realistic channels demonstrating that spatial, time and frequency diversities are efficiently exploited.
- VUT (24):
  - **Development of computationally efficient detection algorithms for MIMO-OFDM systems:**
    As a first step we plan to investigate potential extensions of conventional detection algorithms (designed for the frequency-flat case) to the frequency-selective case. The aim is to devise smart extension that exploit subcarrier correlation in order to reduce computational complexity.
- ETH (26):
  - **Space-frequency codes with limited channel knowledge:**
    We investigate the design of space-frequency codes for MIMO-OFDM systems with no or partial channel knowledge at the receiver. The coding scheme is designed depending on the amount and the kind of training available. In particular, cases between coherent and completely noncoherent coding schemes, termed semicoherent, are explored.

– **Transparent space-time/ -frequency MIMO adaptation layer:**
  The MIMO adaptation layer provides system adaptation to the MISO or MIMO channel, to channel knowledge at transmitter, to the number of antennas, or to spatial multiplexing and diversity gain, decoupled from channel coding such as forward error correction. We investigate coding schemes/structures that:
  * are transparent to the symbol alphabet used in the preceding (sub-) layer;
  * are therefore readily combined with forward error correction and turbo coding;
  * are able to utilize spatial, temporal and frequency diversity;
  * are able to use the potential of rich arrays (antenna arrays with a large number of antennas) with a reasonable and scalable decoding complexity;
  * allow joint use of transmit diversity and spatial multiplexing (e.g., in situations having more transmit than receive antennas);
  * allow to trade diversity gain for spatial multiplexing gain.

- DLR (31):
  – **Diversity increase versus system degradation:**
    Differential modulation/demodulation suffers from a decorrelation of the channel. Such a decorrelation is achieved by cyclic delay diversity (CDD) [20], which actually means an increase of diversity. Therefore, a trade-off between diversity increase and system degradation due to channel decorrelation for differential modulation/demodulation has to be found for OFDM systems.

- CNIT (32):
  – **Development of low complexity space-time receivers for MIMO/OFDM systems:**
    Earlier work concerned joint detectors for single carrier MIMO systems, which operate mainly in the frequency domain and yield a large performance improvement with respect to cancellation techniques (BLAST). These algorithms will be extended to MIMO/OFDM systems, including the design of pragmatic space-time codes for MIMO systems.
  – **Dirty Paper compatible codes**:
    Investigate families of codes that could be used for the “writing on a dirty paper” approach in a broadcast channel scenario (e.g., linear nested block codes). Comparison of such an approach with already known precoding techniques, in addition to investigation of suboptimal solutions.

- KTH (58):
  – **Resource allocation using feedback:**
    Investigate multi-user schemes that exploit different levels of channel feedback, both long-term information in the form of second order statistics and partial short-term information. The goal is to multiplex users both in time, frequency and space to use the available radio resources as well as possible given QoS constraints for each user.

4.4 Large-Scale Multi-User and Multi-Antenna System Analysis

The theory of large random matrices is now recognised as a valuable tool for studying the performance of multiple access transmission systems (such as CDMA and MC-CDMA) and of MIMO systems.

The performance indices of detectors for (MC)-CDMA systems, such as the Signal to Interference and Noise Ratio (SINR) at their outputs, usually depend in a complicated way on the entries of the spreading matrices used in these systems. However, if these matrices are modelled as realizations of certain kinds of random matrices (e.g., independent and identically distributed (i.i.d), Haar distributed, deterministic unitary matrices scrambled by an i.i.d. sequence, and so forth), and if the matrix dimensions increase at the same rate, then it turns out that these indices converge toward deterministic quantities that depend only on the statistical properties of these matrices, and not on their particular realisations ([84], [86]). The evaluation of these limits, based on large random matrix theory, free probability theory and replica analysis, lends considerable insight into the influence of the various relevant parameters on the performance. These parameters include the loading factor, the distribution of the extra-cell interference, and the power allocation among the various users.

The capacity of MIMO systems can also be better understood with the help of these mathematical tools. Here, by considering a probabilistic model for the channel matrix, one has to study in the large dimensional regime the impact of the channel distribution, in terms of correlation between transmit and/or receive antennas, line of sight components, in additional to frequency and/or time selectivity ([17]).

Although some simple situations have been considered in the literature, significant work remains concerning more realistic situations such as CDMA, MC-CDMA and MIMO systems with correlated and/or Rician frequency selective channels, as well as to evaluate and compare the performance of advanced receivers such as multistage and/or iterative receivers. Due to the complexity of the mathematical tools and the diversity of open problems, close collective collaborations between partners are required to get significant results.

Action Plan

- CTTC (9):
  - **Finite sample sizes in multi-antenna systems:**
    We propose to analyse the limitations of classical multi-antenna signal processing architectures under finite sample size situations. When the number of observations has the same order of magnitude as the observation dimension, general statistical analysis (a tool based on random matrix theory) performs much better than classical estimators, allowing for alternative schemes to traditional solutions that are robust to a finite observation window size. We also plan to analyse the finite-sample size limitations of typical signal processing architectures for communications such as channel estimation or spatial filtering schemes.
- Supélec (18):
  - **Synthesis of mathematical tools:**
    A contribution for writing a mathematical state-of-the-art document. The available methods used to describe the behaviour of different random matrix models in the asymptotic regime will be presented in this document.
  - **Cellular uplink communications:**
    Performance analysis of channel estimation algorithms in the large system regime for cellular uplink communications. Study of the impact of the estimation errors on the receiver's performance.

- **Convergence analysis:**
  A SINR convergence study for CDMA and MC-CDMA receivers (in collaboration with CNRS).

- CNRS (19) + FTW (34):

  - **Synthesis of mathematical tools:**
    Contribution to a collaborative work aiming at identifying the system design problems that can be studied using large system analysis , and the mathematical approaches that can be used in order to solve the above problems
  - **Performance analysis of large multi-user CDMA and MC-CDMA systems:**
    1. The asymptotic behaviour of the output SINRs of the most classical detectors has been studied in the case where the code matrix is independent identically distributed (uplink case) or Haar distributed (downlink case). We aim to perform a similar analysis in the case of Walsh-Hadamard matrices scrambled by an independent identically distributed sequence, a model used in the downlink of UMTS-FDD.
    2. Although the SINR converges to a deterministic limit when the spreading factor and the number of users converge to infinity, for a finite size system, the actual SINR fluctuates around the limit. We plan to study the distribution of the fluctuations in order to evaluate their influence on performance.
    3. The asymptotic behaviour of the output SINRs of classical linear detector has been widely studied for synchronous systems. Asynchronous systems are not yet well understood as well as the effects of band limited pulses.
  - **Performance analysis of MIMO systems in the context of Rician channels:**
    The influence of channel distribution on the capacity of MIMO systems has been studied extensively in the context of Rayleigh channels. However, the case of Rician channels and/or frequency selective is less well understood. We therefore plan to study the capacity of large MIMO systems in this context.

- France Telecom R&D (21):

  - **MIMO MC-CDMA:**
    MC-CDMA takes advantages of both OFDM (high spectral efficiency and robustness against multipath effects) and CDMA (multi-access flexibility and low multi-user interference). In fact, OFDM guarantees orthogonality between sub-carriers and multi-carrier symbols while CDMA offers orthogonality between users using Walsh-Hadamard spreading sequences for a synchronous downlink system. In a MIMO context, spatial multiplexing can increase the capacity of the MC-CDMA system and STBC the exploitation of the diversity. Transmitter and receiver schemes will be described. Performrmance over theoretical and realistic channels, including channel estimation, will be provided.

- Eurécom (22):

  - **Contribution to a collaborative work aiming at identifying:**
    a) the system design problems that can be studied using large system analysis;
    b) the mathematical approaches that can be used in order to solve the above problems;

  - **Spectral efficiency with inter-cell interference:**
    The design of infrastructures for CDMA cellular networks is crucial for content providers. We would like to study in more detail the impact of inter-cell interference on the spectral efficiency of downlink and uplink CDMA with refined propagation models taking into account path loss and shadowing. In particular, our aim is to optimise the inter-base station placement for a given geometry and provide a simple rule to deploy a cellular network. The tools are mainly based on random matrix theory using asymptotic (in terms of spreading length and density) arguments.

- UoY (61)

  - **Spectral efficiency of MIMO cellular systems with realistic channel models:**
    An important question which has only recently begun to be considered is the capacity of MIMO celullar systems, considering co-channel interference. Moreover it has been shown that correlated fading can have a significant effect on the capacity of such systems [96], and so such work must make use of realistic MIMO channel models such as are being developed in Dept. 2. Initial work suggests that a significant benefit from the use of MIMO remains in such systems, but many open questions remain, especially when techniques being developed elsewhere in Dept. 1 are used in cellular systems.

4.5 Wideband System Scalability

In order to achieve the higher data rates envisioned for future wireless applications, systems with increasingly larger bandwidths are being considered. Many fundamental knowledge gaps remain, however, concerning how well existing technologies such as CDMA and OFDM scale as the bandwidth of a multi-path fading channel is increased. Recent information-theoretic work [56], [82] shows that large bandwidths over fading multipath channels cannot be effectively utilised by systems that spread the transmitted signal power uniformly over both time and frequency. Instead, peaky signalling schemes, which concentrate the signal power in both time and frequency, can attain channel capacity. What lies behind this phenomenon is that each signalling scheme requires a specific set of channel parameters to be estimated before successful detection can be carried out. Spread-spectrum systems, in particular CDMA, do not scale well when the bandwidth is increased, because channel estimates deteriorate as the bandwidth is increased. This casts doubts on the feasibility of wideband CDMA technology in meeting future wireless system requirements. There is need to study from a fundamental perspective the capacity and signalling problems related to next generation wireless systems to identify if present methods will encounter insurmountable scalability problems.

Another set of wideband system scalability problems surface when we consider cellular networks. The capacity region for a multiple access channels is known and practical solutions to approximate the capacity can be implemented (e.g., algorithms appealing to multi-user water-filling) [16], [94], [89]. For cellular systems, however, where the frequencies of each cell have to be re-used by other cells, the optimum solution is still unclear. In order to achieve optimum cell spectral efficiency, the designer is confronted with a fundamental compromise between a low re-use distance which requires fewer frequency bands, and high re-use distance which generates less co-channel interference, thereby allowing higher link spectral efficiency. These considerations highlight a significant knowledge gap related to the identification of the optimum frequency re-use distance, the choice of multiple access and modulation schemes, and the network topology for such cellular systems.

Some generic lines of research to address the knowledge gaps identified above are information-theoretic capacity estimates of wideband multipath fading channels, design of scalable signalling schemes for point-to-point systems, design of scalable frequency reuse methods for cellular systems, and study of scalability properties of various specific schemes such as multi-band OFDM and multi-carrier CDMA. The multiple antenna versions of these same problems are also of interest. Against this broad background, we have decided to focus our research efforts on the following subjects.

- Ultra Wide band (UWB) Systems.

  Estimating the UWB channel capacity, in particular, for the channel models specified in [10]. Determining the achievable rates by various multicarrier UWB systems, including OFDM, coded OFDM (COFDM), MIMO-OFDM, etc. Variants of the problem with partial channel state information (CSI) at the transmitter will also be considered.

- Wideband Cellular Networks.

  Performance analysis of OFDMA and MC-CDMA for cellular downlink systems with attention to frequency reuse factor. Development of radio resource management methods for both systems. Investigation of synchronous and asynchronous downlinks.

Action Plan

- Bilkent (06)

  – **Capacity in UWB Systems:**
  The notion of a UWB system has become more precise by the recent FCC ruling [27] which opened the frequency range 3.1–10.6 GHz to unlicenced operation subject to certain constraints. There is an ongoing effort by the IEEE 802.15.3a Personal Area Network group for physical layer standardisation of UWB systems. It is of great interest to study the theoretically achievable rates of the UWB systems and the performance of various candidate systems proposed for standardisation. The work begun in [5] in estimating the capacity of IEEE UWB channel models will be continued. The analysis of this channel model is of interest in light of recent information-theoretic work on multipath fading channels which show that, in order to take full advantage of capacity of wideband fading channels, the transmitted signals have to be “peaky” in a certain sense. The immense bandwidth of the UWB channel also suggests, at first, that peaky signals should be used. However, unlike the many other wireless systems where the transmitter is limited by its peak or average power, in the case of the UWB channel, the RF emission regulations constrain only the power spectral density of the transmitted signal in the UWB channel [27]; i.e., the signal power is permitted to grow in proportion to the utilised bandwidth. As a result of this relaxed constraint on transmitter power, it turns out that there exist signalling schemes for UWB channels that are not peaky and that scale well with bandwidth. There is still need to design a signalling system that scales well in terms of achievable rates and implementation complexity. Another conclusion in [5] is that under the target operating conditions for UWB channels, relatively quick estimation of the channel state may be possible, suggesting the use of feedback schemes where the transmitter has partial CSI. We plan to explore this issue further.

- VUT (24):
  - **Capacity of wideband multicarrier transmissions:**
    We aim to extend recent results regarding the single-input-single-output case without channel state information at transmitter and receiver to more general settings (MIMO-OFDM, partial CSI, …).
- ETH (26)
  - **Channel uncertainty in wideband communication systems:**
    Communication at very low available power per Herz of bandwidth is challenging since channel knowledge is difficult to obtain. Current results only deal with the infinite bandwidth limit; the properties of systems operating over a large but finite bandwidth are unclear. We aim to
    - establish design criteria for signaling schemes which take into account realistic constraints (limited peakiness, limited blocklength), and assess the difference between training-based and non-training-based schemes;
    - determine fundamental channel characteristics like the scaling of the degrees of freedom with bandwidth and the shape of the eigenvalue spectrum;
    - determine the impact of these channel characteristics on the performance of the signaling schemes.
- TUA (29):
  - **Coded OFDM for UWB systems:**
    Coded OFDM (COFDM) is well suited as a transmission technique for ultra wideband (UWB) systems, since it allows the exploitation of frequency diversity in an efficient and convenient way. Due to the very low spectral power density in UWB systems, channel estimation is a crucial and challenging task. Therefore, we aim to examine the applicability of UWB COFDM systems by deriving theoretical bounds for the quality of channel estimation and by analysing the effect of imperfect channel estimation on the transinformation. Additionally, we focus on the development of optimal strategies to avoid/cancel different forms of interference like inter-cell, intra-cell and external (narrowband) interference, which will denote a major limitation of future UWB systems. Also, we intend to extend the investigations to multiple antenna (MIMO-OFDM) systems.
- DLR (31):
  - **Cellular systems:**
    Work will be done for OFDMA and MC-CDMA in the area of cellular downlink systems. Hereby, different aspects are taken into account: sectoring for improving the C/I of the system and the capacity; optimisation of the frequency reuse factor; different radio resource management methods for both systems; investigation of synchronous and asynchronous downlinks. Finally both systems, OFDMA and MC-CDMA, will be compared.

4.6 Multi-bit per Hertz coding

The celebrated Shannon theory predicts reliable communications for which power efficiency and bandwidth efficiency can be exchanged in a flexible manner. Future-generation wireless systems will rapidly require simultaneously high power efficiency and high bandwidth efficiency. Today, only a few coding schemes are known that can attain signalling rates above 1 bit/s per Hertz of channel bandwidth, namely trellis-coded modulation and coset codes, multilevel codes, and bit-interleaved coded modulation.

A major problem in coding for very high order modulations (64-QAM or above) is the fact that powerful codes such as turbo-codes and/or LDPC codes are generally designed in a binary field, which may lead to performance degradation caused by the demapping step at the receiver. Trellis-coded modulations have shown the importance of designing codes directly in the constellation space in order to achieve very good performance.

A promising approach to overcome this problem is to use non-binary codes in high order Galois fields. The field order must be equal to or higher than the order of the constellation, in order to avoid the symbol-to-bits demapping step at the receiver. The considered codes should also be flexible with respect to rate adaptation and/or constellation adaptation.

If we stick to powerful binary codes, existing schemes should be enhanced in order to achieve high spectral efficiencies at tolerable error rates.

In a bit-interleaved coded modulation scheme (BICM), iterative information exchange between the demapper and the channel decoder at the receiver improves the performance for high order modulations. Here, Gray mapping may no longer be the optimal choice. A key knowledge gap here is the design of mappings adapted to iterative demapping and to the channel code.

Furthermore, the design of trellis coded modulation (TCM) with iterative decoding techniques should be further investigated and compared to the other bandwidth efficient schemes.

The knowledge gaps in this area therefore include (i) whether emerging techniques or enhancements of well-know coded modulation schemes can be modified to rate-adaptive flexible coding schemes operating over a wide range of real-world scenarios; (ii) the design of non-binary codes in combination with high order modulations; and (iii) the design of mappings for large signal constellations in combination with the channel code for different scenarios and applications.

Action Plan

- GET (17):
  - **Iterative decoding with high order modulation:**
    The combination of non-binary iteratively decoded codes (CTC, BTC and LDPC) with high order modulations (PSK, QAM or multiple transmitters) will be investigated. Non-binary codes are potentially more powerful than their binary counterparts and they open new possibilities for optimising the mapping of non-binary elements of the codes on the modulation elements. Theoretical and implementation aspects will be considered. This activity will have a strong interaction with that proposed in Section 4.1
- CNRS (19):
  - **Galois field LDPC codes:**
    We will study the performance of non-binary LDPC codes on high order modulation (up to 256-QAM), when the LDPC code is built in a Galois field whose order is the same as (or greater than) that of the constellation. This ensures that all mappings of the constellation perform equally, which reduces the optimisation of the receiver to the LDPC code design. Adaptability of the Galois field order will also be considered for applications where puncturing and/or bit loading are employed.

- LNT-TUM (28) + UoE (53):
  - **Optimisation of bit mappings:**
    Application of numerical optimisation schemes to find suitable bit-mappings for QAM- and PSK-modulation employed in bit-interleaved coded modulation with iterative decoding (BICM-ID) [73]. Analysis of the gains in transmission power for BICM-ID schemes employing convolutional and Turbo/LDPC channel codes. Performance and complexity analysis of the optimisation methods.
- CNIT (32):
  - **Bit mapping by set partitioning:**
    Design and performance analysis of reduced complexity detection algorithms for spatial multiplexing systems with high order modulations. The main idea consists in applying the principle of mapping by set partitioning, used in reduced state sequence estimation, to the constellation associated to each transmitted substream.
- UoSo (51):
  - **Interleaved trellis coded modulation:**
    Space-Time Block Coded Inphase-Quadrature phase (IQ)-interleaved Trellis Coded Modulation (TCM) and Turbo TCM (TTCM) schemes were proposed in [58], which are capable of quadrupling the diversity order of conventional symbol-interleaved TCM and TTCM. The increased diversity order of the proposed schemes provides significant coding gains, when communicating over nondispersive Rayleigh fading channels without compromising the coding gain achievable over Gaussian channels. Further open problems are related to the design of similar schemes for dispersive channels.

4.7 Joint (Turbo) Receiver Optimisation

Background

Traditional receiver designs involve separate algorithms for synchronisation, channel estimation, equalisation, multi-user detection, channel decoding, and so forth. The success of turbo decoding and related techniques has inspired joint iterative algorithms where (at least some of) these distinct receiver components exchange soft information such that imperfections in one stage can be alleviated by another; this also favours reduced complexity circuit design by combining tasks on a single chip. Examples include iterative multi-user detection, iterative demodulation of bit-interleaved coded modulation, iterative MIMO detection, and iterative synchronisation. These iterative turbo receivers, if convergent, typically lead to a state of “consensus" of the individual receiver stages regarding the desired information. Initial experimental evidence for such turbo receivers is very promising. However, at present their design is partially somewhat heuristic and major shortcomings are still observed.

Iterative receivers are known to yield only approximate maximum likelihood solutions in general; this can be explained by the presence of loops in their factor graph representations. To complicate matters, while performance improvements of such turbo algorithms are quite manifest in some situations, misconvergence (such as limit cycles, chaos, or numerical singularities) is also observed in harsher communication environments. Simulation evidence [68] further shows that the reliability of the initial estimates or of the a priori information has a critical impact on the performance of such joint iterative receiver algorithms; this is in contrast to classical turbo decoding where little a priori knowledge suffices to ensure convergent iterations. This observation reinforces the need for estimating channel state information (CSI) in a number of iterative/turbo schemes, including the channel impulse response in turbo equalisation, or phase and frequency offsets in turbo synchronisation. A promising approach to turbo processing with partial channel state information uses the EM algorithm for re-estimating the parameters of interest (e.g., [45, 63, 35]). This establishes a link to advanced signal processing algorithms discussed in Section 4.8.

We conclude that present understanding only partially explains the success of turbo methods. The adaptation of information theory tools to describe such iterative algorithms is thus fundamental to the successful design of interconnected receiver components that exchange soft information. Without such knowledge, design principles remain heuristic and open to scrutiny.

Knowledge Gaps

The following key knowledge gaps impeding present-day deployment of iterative joint turbo receivers have been identified:

(i) Theoretical analyses of the convergence and stability of iterative turbo algorithms for various combinations of distinct receiver components and various operating conditions;

(ii) Practical investigations of iterative algorithms where multiple receiver sections exchange information.

(iii) Data-efficient estimators for initial conditions ensuring that the “turbo effect” is triggered;

(iv) Design of computationally efficient soft-input-soft-output (SISO) modules for the individual receiver stages;

(v) Robustness to partial channel state information (CSI) and embedding of re-estimated CSI in the turbo-processor.

Regarding knowledge gap (i), promising approaches might be based on information geometry [40], which lends valuable geometric insights into these iterative algorithms and can also be exploited to accelerate their convergence rate. Alternatively, methods used in statistical mechanics and factor graph/belief propagation networks also might prove useful in this context.

A useful starting point regarding (ii) is to consider joint iterative synchronisation and channel equalisation, two tasks traditionally performed separately, but for which degradations in one severely impact the other. An improved understanding of their interactions in realistic channel conditions will provide guidelines for the design of more sophisticated and robust joint iterative channel estimation and synchronisation modules (knowledge gap (iv)) that appeal to the turbo principle.

Concerning knowledge gap (v), algorithm design thus far has assumed perfect channel state information. Some studies (e.g., [83, 26]) have modified the outer processor when only partial CSI is available. Design of outer processors (knowledge gap (iv)) that are optimal in a maximum likelihood sense is desired, and sub-optimal versions should be derived based on a better understanding of the underlying approximations.

Extensions to more advanced configurations (knowledge gap (ii)), such as iterative multi-user decoding or joint channel-state-estimation/decoding, would logically build on the expertise to be acquired from the initial phases of this work.

Action Plan

The plans of the individual partners to fill the above knowledge gaps are described in more detail below (the knowledge gaps addressed are listed in brackets).

- GET (17):
  - **Information geometric description of iterative receivers** [(i), (iii)]
    Development of information geometry description of iterative receivers, which do not necessarily appeal to asymptotic large scale system results. Aim to isolate which signal-plus-interference-to-noise ratios, and which initial conditions, lead to a convergent system.
- CNRS (19):
  - **Novel turbo synchronisation schemes** [(ii)–(v)]
    Investigation of novel turbo synchronisation schemes that iteratively estimate the carrier phase and the data. This turbo receiver structure will be based on block turbo codes. Performance at low SNR will be investigated. In addition, the robustness to imperfect CSI will be studied, aiming at understanding the influence of SNR on triggering the turbo-processor as well as on the number of iterations. Development of new algorithms with a modified outer processor to identify performance limits and required initial conditions.
- VUT (24):
  - **Efficient hard and soft decoding** [(i), (v)]
    Development of efficient hard and soft decoding algorithms for large linear data models with high-order modulation (e.g., in MIMO and multi-user contexts). The goal is to develop close-to optimum algorithms with reduced complexity and to study their impact on turbo-like receivers. We further plan to work on the information geometric analysis and acceleration of iterative receiver structures.
- TUA (29):
  - **Joint synchronisation and decoding at low SNR** [(ii), (iv)]
    Iterative decoding schemes are very power efficient and therefore well suited for scenarios with low SNR. In such scenarios, accurate frequency and carrier synchronisation, a prerequisite for successful iterative decoding, is challenging. Furthermore, the number of pilot symbols in transmission schemes with short data packets is limited. Hence, we plan to develop optimal iterative joint carrier synchronisation and decoding algorithms in order to exploit the actual data symbols for the task of synchronisation and thereby minimise the pilot symbol overhead.
- DLR (31):
  - **Turbo structures with advanced modulation** [(ii), (iv), (v)]
    Iterative receiver structures with different modulation schemes and *a posteriori* probability (APP) greater than a specific threshold outperform conventional modulation schemes. These new schemes will be investigated in the context of coded MC-CDMA systems. Channel estimation will be included into the iterative receiver structure since this allows one to exploit the additional hard or soft symbols provided by the decoder and hence is expected to improve performance under realistic channel conditions. In particular, performance

gains and robustness of iterative channel estimation algorithms will be investigated for coded MC-CDMA systems.

- CNIT (32):
  - **Frequency-domain block iterative receivers** [(ii), (iv)]
    Turbo decoding and turbo equalisation are familiar tools for enhancing receiver performance. Their high complexity, however, can still impede their implementation. As a compromise between performance and complexity we propose a block iterative equaliser-decoder algorithm which operates mainly in the frequency domain.
- FTW (34) + FT (21):
  - **Iterative multi-user decoding with channel estimation** [(i), (ii)]
    We plan to extend the convergence analyses of iterative multi-user decoding in systems with many users to include channel estimation in the iterative loop.
- PUT (36):
  - **Carrier phase synchronisation** [(i), (iv)]
    Development of new structures of carrier phase synchronisation schemes for receivers with turbo coded signals. The schemes will be based on iterative processing with the use of the soft information provided by the turbo decoding algorithm. The aim is to develop efficient and robust schemes maintaining reduced complexity. Performance of the schemes will be investigated.
  - **Iterative multicarrier equalisation** [(ii), (iv)]
    Studies of new iterative equalisation schemes for single and multicarrier transmission, in the time and frequency domain. Complexity, performance and robustness to channel estimation errors of these schemes will be investigated. In addition, research on joint channel estimation and turbo equalisation will be conducted, as well as the analysis of turbo equalisation for higher order modulations.
- UCL (38) + UGent (37):
  - **Parameter estimation in turbo synchronisation** [(i), (ii), (iv), (v)]
    Investigation of turbo synchronisation and parameter estimation, focusing on carrier phase and timing recovery for SISO systems, as well as CSI/noise estimation for CDMA and MIMO coded systems. Convergence issues will be studied in the light of belief propagation and factor graphs.
- AAU (41):
  - **Joint multi-user decoding and channel estimation** [(ii), (iv), (v)]
    Advanced iterative receivers for joint multi-user decoding and channel estimation are requested to support large system loads and need to be robust against channel estimation errors. Recently, we derived a joint interference cancellation and channel estimation scheme based on an extended version of the SAGE algorithm. The scheme exchanges soft information with a data decoder in an iterative fashion in a DS/CDMA scenario. Investigations concentrate on the influence of the system load on the performance and the kind of soft information to be exchanged between this so-called soft-input soft-output (SISO)-SAGE algorithm and the data decoder.

- Chalmers (42):
  - **Turbo receivers and the EM algorithm** [(i)–(v)]
    We have in the past designed iterative schemes for channel estimation, synchronisation, and channel decoding (turbo codes, convolutional codes, Hadamard codes). We want to set these and similar schemes on a more solid theoretical basis by formalising the design and analysis methods, e.g., by appealing to similarities with the EM algorithm. The goal with this study would be to give (at least partial) answers to the key knowledge gaps (i)–(v) outlined above. Clearly, this study also touches the knowledge gaps described in Section 4.8 (Advanced Signal Processing Algorithms for Wireless Communications).
- UoSo (51):
  - **Turbo coding for wideband dispersive channels** [(ii), (iv)]
    We have previously proposed various source/video-coding, channel-coding and modulation schemes [33, 30, 34, 31, 32] that achieve significant coding gains, low error floors, and low latency without bandwidth expansion via joint iterative decoding by exchanging extrinsic information. Our future research targets at rendering these sophisticated turbo transceivers applicable to wideband dispersive channels. Furthermore, we plan to adapt the reduced complexity turbo detection scheme in [30] to space-time trellis coded systems and to improve the decoding of space-time block codes augmented by sphere packing [2] and channel coding by performing demapping and channel decoding in an iterative manner.
- UoY (61)
  - **Analysis of turbo joint carrier phase estimation and decoding** [(i), (ii)]
    Another function where the turbo principle has been very successfully applied is joint decoding and carrier phase estimation. This provides a basis for the comparison of different turbo schemes, including the EM algorithm and a-priori aided (APPA) techniques. Initial results show that there are fundamental differences between these approaches which mean that the convergence criteria which apply to the former do not necessarily carry over to the latter, while under some circumstances the latter may converge more rapidly.

4.8 Advanced Signal Processing Algorithms for Wireless Communications

Traditional wireless technologies are confronted with new challenges in meeting the ubiquity and mobility requirements of cellular systems. Hostile channel characteristics and limited bandwidths in wireless applications provide key barriers that future generation systems must cope with. Advanced signal processing methods, such as

- The expectation-maximisation (EM) algorithm;
- The SAGE algorithm;
- The Baum-Welch algorithm;
- Per-Survivor processing;
- Kalman filters and their extensions;
- Hidden Markov modelling;

- Sequential Monte Carlo filters;
- Stochastic approximation algorithms;
- Sphere decoding and convex relaxation techniques (semidefinite relaxation) for detection.

in collaboration with inexpensive and rapid computing power provide a promising avenue for overcoming the limitations of current technologies. Applications of advanced signal processing algorithms mentioned above include, but are not limited to, joint/blind/sequence detection, decoding, synchronisation, equalisation as well as channel estimation techniques employed in advanced wireless communication systems such as OFDM/OFDMA, Space-Time-Frequency Coding, MIMO, CDMA and with Multi User Detection, Time- and Frequency-Selective MIMO channels. Especially, the development of suitable algorithms for wireless multiple-access systems in non-stationary and interference-rich environments presents major challenges to us. While considerable previous work has addressed many aspects of this problem separately, e.g., single user-channel equalisation, interference suppression for multiple access channels and tracking of time varying channels, the problem of jointly combating these impairments in wireless channels has only recently become significant. On the other hand, the optimal solutions often present a prohibitively high computational complexity, impeding thus their implementation. The statistical tools offered by the advanced signal processing techniques above have provided a promising new route for the design of low complexity signal processing algorithms with performance approaching the theoretical optimum for fast and reliable communication in the highly severe and dynamic wireless environment.

Although over the past decade such methods have been successfully applied in a variety of communication contexts, many technical challenges remain in emerging applications, whose solutions will provide the bridge between the theoretical potential of such techniques and their practical utility.

Key knowledge gaps here concern:

(i) Theoretical performance and convergence analyses of these algorithms;

(ii) New efficient algorithms need to be worked out and developed for some of the problems mentioned above;

(iii) Computational complexity problems of these algorithms when applied to on-line implementations of some algorithms running in the digital receivers must be handled;

(iv) Implementation of these algorithms based on batch processing and sequential (adaptive) processing depending on how the data are processed and the inference is made has not been completely solved for some of the techniques mentioned above;

(v) Some class of algorithms requires efficient generation of random samples from an arbitrary target probability distribution, known up to a normalising constant. So far two basic types of algorithms, the Metropolis algorithm and the Gibbs sampler have been widely used in diverse fields. But it is known that they are substantially complex and difficult to apply for on-line applications. There are gaps for devising new types of more efficient algorithms that can be effectively employed in wireless applications.

(vi) Although the research on Sequential Monte Carlo signal processing has recently started, many optimal signal processing problems found in wireless communications, such as mitigation of various types of radio-frequency interference, tracking of fading channels, resolving multipath channels dispersion, space-time processing by multiple transmitter and receiver antennas, exploiting coded signal structures represent few problem waiting for to be solved under the powerful Monte Carlo signal processing framework.

Action Plan

The following research activities were proposed by the several NEWCOM groups to apply the advanced signal processing algorithms to a variety of wireless communications systems.

- Technion (05):
  - **Multi-user receivers for detection of code-division multiple-access (CDMA) signals:** Recent developments in optimisation theory has lead to an intensive search for advanced signal processing techniques for multi-user detection. Multi-user receivers try to mitigate the effect of the multiple-access interference (MAI) and the background noise. One of the open questions in this important area is the problem of robust multi user detection, i.e., the design of the detection algorithms in the presence of signature uncertainties. In this research, new robust detection algorithms including linear detectors, suboptimal relaxation of the optimal ML detectors, and optimal detection schemes will be planned to be investigated. For each of these it is planned on developing a robust version under different models of uncertainty. This research effort is conducted by Ami Wiesel and Dr. Yonina Eldar. Potential NEWCOM partners on this study, with whom contacts have been established are: Prof. Helmut Bölcskei of ETH, and Prof. Mats Bengtsson of KTH, Sweden.
- IŞIK (07):
  - **Channel Estimation Based on Stochastic Channel Modelling in OFDM:** In a wireless orthogonal frequency division multiplexing (OFDM) systems over a frequency selective fading, channel variations arise mainly due to multipath effect. Consequently, channel variations evolve in a progressive fashion and hence fit in some evolution model. It appears that basis expansion approach could be natural way of modelling the channel variation. Fourier, Taylor series, and polynomial expansion have played a prominent role in deterministic modelling. As an alternative to the deterministic approaches, the variation in the channel can be captured by means of a stochastic modelling. Note that, the random process can be represented as a series expansion involving a complete set of deterministic vectors with corresponding random coefficients. This expansion therefore provides a second order characterisation in terms of random variables and deterministic vectors. There are several such series that are widely in use. A commonly used series is the Karhunen-Loève (KL) expansion. In this work, we will rely on the KL basis expansion of stochastic channel model to perform pilot aided channel estimation in OFDM systems. In the case of KL series representation of stochastic channel model, a convenient choice of orthogonal basis set is one that makes the expansion coefficient random variables uncorrelated. When these orthogonal bases are employed to characterise the variation of the channel impulse response, uncorrelated coefficients indeed represent the channel. Therefore, KL representation allows one to tackle the estimation of correlated channel parameters as a parameter estimation problem of the uncorrelated coefficients. Exploiting KL expansion, the main contribution of this work will be to propose computationally efficient, pilot-aided channel estimation algorithms. Moreover, optimal rank reduction can also be achieved

by exploiting the optimal truncation property of the KL expansion resulting in a smaller computational load on the estimation algorithms.

- **Adaptive Combined Kalman Receiver for OFDM Systems with Transmit Diversity in Mobile Wireless Channels:**
This work focuses on the important issue of joint channel tracking and decoding in the ST-OFDM transmitter diversity setting. We will propose adaptive Kalman receiver for both channel tracking and subsequent equalisation which are combined in the coupled estimator structure. The stochastic approach will be used to describe channel's variations in a general vector AR framework. Fortunately, the AR modelling lends itself to a state-space representation that enables the application of Kalman filtering for tracking channel variations. We will therefore propose Kalman filtering to derive minimum variance estimators for fading coefficients yielding an adaptive channel tracking algorithm. However, this requires the knowledge of the transmitted symbols. This implies that an iterative method should be sought to obtain alternatively either channel or transmitted symbols. To complete detection-tracking algorithm for transmit diversity OFDM systems with the distributed training, a linear Kalman filter equalisation technique is therefore proposed for the detection of transmitted symbols.

- **Sequential Signal Processing Framework:**
Sequential Monte Carlo methodologies, recently emerged in statistics, have provided a promising new paradigm for the design of low-complexity signal processing techniques for fast and reliable communication in highly severe wireless environment. In this work, we will provide solutions to joint/blind/sequence detection, synchronisation, equalisation as well as channel estimation techniques employed in OFDM/OFDA, Space-time-frequency coded and MIMO systems, under the Bayesian framework with sequential Monte Carlo methodologies.

• UPC (08):

- **Signal processing algorithms to design robust communication systems:**
The objective is to review and propose different signal processing algorithms that are able to include robustness capabilities in a communication system, in such a way that the obtained design is less sensitive to the errors in the presumed model during the design, such as the noise in the channel estimate, among other effects. Development of advanced signal processing algorithms suitable for the specific problem of the presence of errors in the presumed theoretical model. Design of techniques based on the Bayesian and the "maximin" philosophies modelling these errors and exploiting the capabilities provided by convex optimisation theory. Different sources of errors will be analysed and identified, such as the noise form the channel estimation process, the quantisation of the channel estimate, the quantisation of the signal samples due to the use of DSP's, etc. The attention will be focused on the selection of the signal processing algorithms that best allow to solve the problems produced by each error source. Besides, the combination of different robust signal processing algorithms will be studied, and the general case corresponding to a system with multiple transmit and receive antennas will be analysed.
- **Advanced algorithms to design robust multi-user communication systems:**
The objective is to derive advanced algorithms to design multi-user communication sys-

tems, in which all the terminals and base stations or access points are allowed to have multiple antennas, and the channel is assumed to be known at both the transmitter and the receiver. The extension of these algorithms to include robustness capabilities will be also considered. Text: Advanced algorithms for the joint design of several transmitters and receivers having multiple antennas in a multi-user scenario. In case that the channel is assumed to be known at all the terminals and base stations or access points, then joint transmit-receive beamforming designs can be employed. The optimum solution cannot be found in closed-form and, consequently, the application of other heuristic techniques, such as simulated annealing, will be considered to solve the stated optimisation problem. The errors in the presumed model and the channel state information will also be considered to extend the algorithms and obtain robust multi-user solutions less sensitive to these errors, that allow to implement them in a realistic scenario.

- CNRS (19):
  - **Position estimation using sequential Monte Carlo filters:**
    Kalman filters and sequential Monte Carlo filters have been used for estimating the position of a vehicle within Global Positioning System. The particular structure of the navigation equations has afforded implementing efficient algorithms using Rao-Blackwell techniques. Different sequential schemes have been studied and the mean square errors of the estimates has been compared to the corresponding Cramér-Rao lower bounds. Development of new algorithms to mitigate interference and multipath effects are under consideration (see also Sec. 4.10)
- Eurécom (22):

  Parameter Estimation for CDMA Systems

  CDMA systems are a prime example of systems in which it is quite difficult to estimate parameters (channel, interference covariance, etc.) needed for receiver design due to the fairly large number of parameters involved (due to the large spreading factor) and due to the relatively few symbol periods of data available for the estimation (again, due to the spreading, and mobility). Standard receiver techniques proceed to a design in which perfect parameter values are assumed, which are then plainly substituted by their estimated values, without taking estimation errors into account. Such an approach is acceptable when good quality parameter estimates can be obtained, but this is often not the case in CDMA systems, and will be less and less the case in future broadband systems. We plan to investigate the following aspects:

  - *Robustification of receivers accounting for parameter estimation errors*. We focus in particular on Linear MMSE type receivers. Standard adaptive filtering algorithms are typically suggested for tracking time-varying quantities in wireless communications, the two main workhorses being the LMS and RLS algorithms. These algorithms typically have only a single parameter to adjust the trade-off between lag noise and estimation noise in tracking time-varying parameters. Typical time-varying filters to be estimated are the channel impulse response and equalisers. The temporal variation in these quantities encountered in wireless communications is actually quite structured, for instance different parts of the filter may vary according to different speeds. Hence the development of more specific adaptive filtering algorithms is warranted.

    The following investigations will be pursued:

  - *Bayesian-based parameter variation models*. We aim to develop LMS-style and RLS-style adaptive filtering techniques that account for parameter variation models in a Bayesian framework. The goal is also to keep computational complexity modest, while improving performance.

- ETH (26):
  - **Sphere Decoding:**
    Sphere decoding has been identified as a promising means to perform maximum likelihood (ML) detection in MIMO or multi-user CDMA settings. However, the algorithm has mostly been considered with a DSP or general purpose processor implementation in mind. We investigate what changes on the algorithmic level need to be made to enable high-performance VLSI implementations, and how suboptimal solutions to the ML decoding problem can lead to even more efficient solutions.
  - **Efficient Equalisation:**
    Computational demands for MIMO OFDM increase with the number of tones and drastically with the number of antennas. Current algorithms for channel equalisation have a complexity that increases with the number of tones, even though the tones may be highly correlated. We propose to make use of the correlation in frequency domain to find algorithms of reduced complexity that allow fast and efficient equalisation for MIMO OFDM.

- LNT-TUM (28):
  - **Analysis of the memory requirements for novel sequential multi-user-detection algorithms:**
    Detailed investigations addressing the trade off between required memory and system performance are intended.

- DLR (31):
  - **Criteria for interference in a CDMA network applying joint layer optimisation:**
    The interference between different users is variable and unique due to the different positions in a cell, channel conditions and the demands of the user. Criteria for a joint layer (1/2) optimisation will be derived and extended.

- UCL (38) + UGent (37):
  - **Turbo synchronisation and parameter estimation:**
    Turbo synchronisation and parameter estimation will be studied with a unifying formalism by means of the Expectation Maximisation concepts, with attention on the interaction of soft information.

- AAU (41) + FT (21):
  - **Iterative joint data detection and channel estimation (JDE):**
    It has been shown that iterative joint data detection and channel estimation (JDE) based on the EM/SAGE algorithms has a number of appealing features: These schemes i) are near-far resistant; ii) are robust against channel estimation errors, iii) exhibit fast convergence rate, and iv) only need a few pilot symbols for the receiver to converge [43]. To support an increasing number of users and wideband services in the future, ongoing research focuses

on deriving efficient algorithms for JDE that exploit in addition the spatial domain by employing multiple-transmit and multiple-receive antennas.

- UoSo (51):

  - **Adaptive Space Time Block Coding (ASTBC) design**
    There are numerous STC designs in the literature, which aim for satisfying different design objectives. It is possible to design a full-rate, full-diversity Adaptive Space Time Block Coding (ASTBC) scheme based on the Singular Value Decomposition (SVD) for transmission over Rayleigh fading channels. However, at the time of writing this is only possible, if the number of receive antennas, N_r equals to N_t, namely the number of transmit antennas. Hence further research is required for circumventing this problem. Furthermore, the ASTBC-SVD scheme may achieve an additional coding gain due to its higher product distance with the aid of using a block code. In conjunction with SVD, the "water-filling" approach can be employed for adaptively distributing the transmitted power to the various transmit antennas according to the channel conditions, in order to further enhance the attainable performance. Since a codeword constituted by N_t symbols is transmitted in a single time slot by mapping the N_t symbols to the N_t transmit antennas in the spatial domain, the attainable performance of the ASTBC-SVD scheme does not degrade, when the channel impulse response values vary from one time slot to the next. Hence, the proposed ASTBC-SVD scheme [62] is attractive in the context of both uncorrelated and correlated Rayleigh fading channels. Further open problems are related to the side-information signalling between the receiver and transmitter.

  - **Development of wireless MIMO transceivers:**
    A number of channel capacity formulae have been provided in the literature for various MIMO schemes, but nonetheless, there are numerous scenarios, which have not been considered at the time of writing. For example, general formulae were derived for the capacity evaluation of MIMO systems using multi-dimensional signal sets, different modulation schemes and an arbitrary number of transmit as well as receive antennas. It was shown that transmit diversity is capable of narrowing the gap between the capacity of the Rayleigh fading channel and the AWGN channel. However, since this gap becomes narrower when the receiver diversity order is increased, for higher-order receiver diversity the performance advantage of transmit diversity diminishes. A MIMO system having full multiplexing gain has a higher achievable capacity, than the corresponding MIMO system designed for achieving full diversity gain, provided that the channel SNR is sufficiently high. Given these formulae [61], it is of high interest to develop wireless MIMO transceivers that are capable of approaching these capacity estimates.

  - **Novel multilevel CDMA receivers based on genetic algorithms:**
    Novel multi-user CDMA receivers based on genetic algorithms have a high potential in terms of reducing the complexity of Verdu's optimum MUD. They are also capable of jointly estimating the transmitted symbols and fading channel coefficients of all the users. Using exhaustive search, the maximum likelihood (ML) receiver in synchronous CDMA systems has a computational complexity that is exponentially increasing with the number of users and hence is not a viable detection solution. Genetic algorithms (GAs) are well known for their robustness in solving complex optimisation problems. Based on the ML

rule, GAs are developed in order to jointly estimate the users' channel impulse response coefficients as well as the differentially encoded transmitted bit sequences on the basis of the statistics provided by a bank of matched filters at the receiver. However, the specific choice of the GAs used requires further optimisation efforts [91, 34].
A spatial diversity reception assisted multi-user CDMA detectors based on genetic algorithms (GAs) are more sophisticated than their counterparts dispensing with diversity reception. In [92] two different GA-based individual-selection strategies are considered. In our first approach the so-called individuals of the GA are selected for further exploitation based purely on the sum of their corresponding figures of merit evaluated for the individual antennas. According to our second strategy, the GA's individuals are selected based on the concept of the so-called Pareto optimality, which uses the information from the individual antennas independently. Computer simulations showed that the GAs employing the latter strategy achieve a lower BER as compared to the former strategy. For a 15-user GA-assisted system employing a spreading factor of 31 a complexity reduction factor of 81 was achieved at a performance identical to that of the optimum multi-user detector using full search.
In an asynchronous DS-CDMA system a specific bit of the reference user is interfered by two asynchronously arriving surrounding bits of all the other users supported by the system. Hence for optimum multi-user detection, the entire input bit sequence influencing the current bit-decisions must be considered, which results in a high detection delay as well as a high receiver complexity. Suboptimal multi-user detection methods have been proposed based on a truncated observation window, in which the so-called 'edge' bits are tentatively estimated by some other means. Using a similar approach, a multi-user detector is developed in this contribution which invokes genetic algorithms (GAs), in order to estimate both the desired bits as well as the edge bits within the truncated observation window. Using computer simulations, we showed that by employing GAs for improving the estimation reliability of the edge bits, our proposed multi-user detector is capable of achieving a near-optimum bit error rate performance, while imposing a lower complexity than the optimum multi-user detector [34, 93]. The related open problems are in the area of improving the choice of the GA's objective function, the employment of MIMO-aided performance improvements, etc.

- UoE (53):
  - **Quantisation of Soft Outputs of Optimal and Suboptimal Constituent Decoders in Iterative Decoding Schemes:**
    In various applications the use of optimal APP algorithms such as BCJR is unfeasible due to complexity, e.g., caused by high memory of convolutional codes. Moreover, complexity and memory requirements are high due to the use of unquantised real-valued bit-based soft-information (L-values) in popular iterative decoding schemes. In the project we will develop good quantisers for the soft-outputs processed in iterative decoding and multi-user detection schemes. We will analyse of trade-off between decoding performance and quantiser accuracy/memory requirements and we will also consider suboptimal decoding algorithms.
- KTH (58):
  - **Complexity Reduction of Sphere Decoding:**

The expected complexity of the sphere decoding algorithm has recently been shown to be exponential (in contrast to previous belief). Still for all reasonable problem sizes it is at least as fast as other algorithms with proven polynomial complexity, such as the semidefinite relaxation. We will further investigate the complexity and detection performance of these and related algorithms.

4.9 Multi-user Space-Time Coding

Cellular wireless systems generally comprise multiple terminals or users that transmit to a central access point or base station (uplink or multi-access channel) and vice versa (downlink or broadcast channel). Understanding the information-theoretic performance limits of such systems and designing transmit/receive schemes (coding and signal processing) is an area with many challenging open questions. In view of future demands for higher data rates and improved link quality, we will focus, in this part of the project, on wideband multi-user systems with *multiple antennas both at the terminals and the access point (MIMO technology)*.

Practical wireless systems often employ multi-access and broadcast schemes that decompose the multi-user system into a set of parallel single-user links. This decomposition can be attained by assigning disjoint subsets of the available time interval (Time Division Multiple Access: TDMA) or the available frequency band (Frequency Division Multiple Access: FDMA) to different users. In CDMA-based systems, separation between users is achieved by assigning different spreading codes to different users. Achieving capacity in multi-access and broadcast fading channels, however, requires that all users collide in time and frequency [28, 6, 8, 88]. In the uplink, a fully collision-based signalling strategy induces high receiver complexity due to the need to separate the individual users' signals at the access point. In the downlink, collision-based schemes lead to interference at the individual terminals which requires sophisticated interference cancellation schemes. Consequently, practical system design should aim at minimising the amount of collision while sacrificing a minimum amount of system capacity. A critical knowledge gap related to the problems described above is the development of deep understanding of the trade-off between the amount of user collision in signal space (time, frequency, code space) and the corresponding capacity region, both for uplink and downlink under varying assumptions on channel state information. In lieu with these important questions is the problem of multi-user space-time code design both for the multi-access channel and the broadcast channel.

CDMA and multicarrier (MC)-CDMA is a communication scheme of great practical importance that by design operates with collision between users in time and in frequency. In contrast to the more information theoretic oriented approach above, we are here interested in system parameters which are directly linked to the performance of CDMA cellular systems, such as the number of users per chip, the delay spread, the affordable decoding complexity, and the tolerable impact of inter-cell interference. We want to focus particularly on the impact of these parameters on the performance of a scheme called Large Area Synchronised (LAS) CDMA [60], for which the optimal trade-offs between the above-mentioned parameters are not yet fully established. We also spotted knowledge gaps in the implementation of iterative decoding algorithms. Since joint MU-decoding is optimal but computationally very costly, we are interested in algorithms which achieve fast interference cancellation with a minimum number of steps.

If channel state information is available at the transmitters, multi-user systems can unfold a particular advantage. The spatial distribution of users allows a system designer to exploit multi-user diversity [23]. Information theoretically optimal transmission schemes which are known for fading multi-access channels [85] are unsatisfying for practical application since they are unfair to users in bad channel conditions. Power loading and scheduling algorithms must be studied in order to find a suitable trade-off between optimal schemes and constraints imposed by requirements of individual users.

Action Plan

- CTTC (9):
  - **MIMO bit allocation strategies:**
    We propose to investigate bit allocation strategies optimised for MIMO multi-user scenarios, in combination with different scheduling alternatives. These spatial bit allocation algorithms will be extended to the time-frequency dimensions, and the balance between performance and complexity, between performance and signalling, and between global vs. individual needs will be addressed.
- CNRS (19):
  - **Linear periodic time-varying filters:**
    Investigations of new access methods based on Linear Periodic Time Varying filters (LPTV) or Periodic Clock Changes [12] and associated multi-user detection techniques [19].
- ETH (26):
  - **Variable collision multi-accessing and broadcasting:**
    Based on previous results in [88], we plan to develop a unified framework for multi-accessing and broadcasting with a variable amount of collision in signal space (time, frequency, code space). In particular, based on previous work in [66], we also plan to take into account out-of-cell interference and develop optimum "hopping patterns" or more generally optimum signal space dimension assignment (time, frequency, code space) patterns. The corresponding assignment strategies will be evaluated both from an ergodic as well as an outage capacity point of view. We expect that the results corresponding to outage capacity will shed light onto the code design criteria for MIMO multi-access and broadcast channels. In particular, we plan to identify under which conditions joint code design across users in the uplink leads to significant performance improvements over the (more simple) approach of having the individual users employ single-user space-time codes. A related question for the downlink is under which conditions superposition space-time coded systems require joint code design across users rather than simply using superposition coding with single-user component codes.
  - **Joint cooperative diversity and scheduling:**
    MIMO wireless systems require a propagation environment with rich scattering to exploit spatial multiplexing gains. Very recently the MIMO concept has been extended to cooperative signaling in order to relax the rich scattering requirement. We will extend the benefits of cooperative diversity, channel adaptive scheduling and spatial multiplexing (MIMO) into a low mobility environment with poor scattering and with heterogeneous nodes.
- DLR (31):
  - **Soft interference cancellation and turbo processing:**
    Enhanced MC-CDMA receivers use multi-user detection algorithms to improve the system

performance. Soft-interference cancellation (SIC) is one of the representatives of these algorithms. However, when using SIC with conventional Gray mapping at the modulation stage, it turns out that almost no improvement can be achieved after the first cancellation iteration. Due to the close relation of SIC with turbo decoding/detection, we should investigated whether it is possible to benefit from the 'turbo-effect' when using more suitable modulation mappings.

- CNIT (32):
  - **Adaptive bit and power loading:**
    Bit and power loading techniques applied to OFDM systems offer the possibility to enhance system performance or throughput. In time varying wireless channels, modem parameters have to be dynamically modified according to the channel state information (CSI) provided by the receiver. We propose the design of adaptive bit allocation algorithms to reduce the modem complexity and the CSI signalling overhead. In this context, particular attention must be paid to channel estimation errors and CSI update rate effects on the performance.
- UoSo (51):
  - **Large area synchronised CDMA:**
    Large Area Synchronised (LAS) CDMA known as LAS-CDMA and MC LAS DS-CDMA were shown to exhibit significantly better performance than traditional random code based DS-CDMA systems in a relatively low chip-rate scenario, provided that all users operate in a quasi-synchronous manner [60]. As the chip-rate increases, the number of resolvable paths also increases, which will impose a performance degradation on LAS-CDMA. However, MC LAS DS-CDMA extends the chip-duration by a factor corresponding to the number of subcarriers and hence avoids the associated performance degradation. Unfortunately, the limited number of available LAS codes having a certain interference-free window (IFW) width suggests that the employment of LAS-CDMA is beneficial in a low-user-load scenario, where a near-single-user performance can be achieved without a multi-user detector. There are numerous related knowledge gaps in the design of such attractive codes exhibiting an IFW, amongst others the analytic description and modelling of the system. As a price to be paid for having an IFW, these codes typically exhibit a higher cross-correlation with other codes outside the IFW, which potentially degrades the achievable performance, when the propagation delays are high. Furthermore, these codes require accurate adaptive timing advance control for the sake of maintaining quasi-synchronous reception at the BS, despite the different propagation delays experienced by the different mobiles.
- UoY (61)
  - **TR-STBC for multi-user MIMO WCDMA systems:**
    Time reversal space-time block coding [53] allows Alamouti STBC to be applied to CDMA systems on frequency-selective fading channels. However when used with a conventional Rake receiver its performance may suffer due to inter-path interference. However for CDMA systems using orthogonal spreading sequences chip equalisation provides an attractive means for mitigating this.
  - **Turbo-PIC receivers for MIMO CDMA and TDMA systems:**
    The turbo-principle is effective in multi-user systems to allow the cancellation of multiple access interference, and when combined with space-time turbo-coded bit-interleaved coded

modulation can approach the single user bound in MIMO CDMA systems, even when approaching full system load. Open problems remain in the performance of this scheme in cellular systems, and in its application to TDMA systems.

4.10 User Mobility Tracking and Handoff Algorithms

Third generation (3G) wireless systems promise hierarchical coverage, seamless roaming, increased data rates, and support for multimedia connections. One of the most important problems for 3G wireless service is handoff management. In classical networks, handoff is the process whereby a mobile terminal communicating with one base station is switched to another base station during a call. In heterogeneous networks, handoff should be extended to switch users from one system to another (inter-system handoff). Conventional ad-hoc approaches compare the absolute and/or relative signal strength measurements with some predetermined threshold. Recently, new classes of handoff algorithms have been developed based on various optimisation criteria, with very simple underlying signal models which do not take into account the user mobility.

Such techniques keep track of a user's location while roaming, in order to co-ordinate cell transitions and global resource allocation. Mobility tracking uses variants of triangulation by comparing a user's pilot signal strengths and propagation times at two base stations. Tracking these important parameters is a nonlinear dynamic system estimation problem, for which the main solution is presently the extended Kalman filter, which can suffer divergence due to nonlinear interactions. Sequential Monte Carlo methods would appear better suited to this task, but much further work is necessary to overcome knowledge gaps concerning: (i) nonparametric estimators in key algorithmic steps; (ii) dependence on statistical priors which may not be available in practice; and (iii) inadequate modelling of the shadow process which confounds mobility tracking.

Action Plan

- UPC (8):
  - **Timing and angle estimation using smart antennas:**
    The conventional methods for wireless positioning are based on the estimation of direction-of-arrival (DOA), time-of-arrival (TOA) or time-difference-of-arrival (TDOA) at a convenient number of base stations. The use of smart antennas (both in diversity and beamforming configurations) offers increased potential in the task of locating user equipment since better delay estimation is obtained, and DOAs may be determined. New timing and angle estimation algorithms taking advantage of the use of smart antennas will be developed.
  - **Unbiased position estimation:**
    The estimation accuracy is limited by the complicated propagation conditions imposed by the wireless channel, such as multipath, delay spread of the channel impulse response, and non-line-of-sight (NLOS) situations, due to transmitted signal blocking. In these situations, the estimation of the first arrival, which bears information related to the position of the mobile terminal, is biased. The feasibility of advanced signal processing techniques to furnish unbiased position estimates will be analysed, including high resolution estimation, Kalman filtering, and other advanced techniques (cf. Sec. 4.8).
  - **Location updating using fuzzy logic control:**
    Fuzzy logic control lends itself to nonlinear, time-varying and ill-defined systems successfully and efficiently. That is, fuzzy logic control is capable of making real-time decisions,

according to incomplete information. Therefore, fuzzy logic control can be used for a location-updating scheme for hand-off that takes into account diverse criteria such as location, received power levels, and consumed bandwidth at each base station, among others.

- Eurécom (22):
  - **Wireless positioning parametrisation in terms of the position itself:**
    A recent contribution [4], shows that parameterising the positioning problem directly in terms of the mobile position leads to an estimation performance that is drastically improved at low signal to interference plus noise ratio (SINR). The usual approach is a two-step procedure in which parameters such as delays and possibly angles are estimated in a first step. In a second step these parameter estimates are used to determine the mobile position via a least-squares fitting problem. The problem is that this two-step approach shows a breakdown behaviour that sets in at an SINR that is not that low. A direct one-step approach in which delays and other parameters get parametrised directly in terms of the mobile position leads to a breakdown behaviour that sets in at much lower SINR. We propose to investigate this behaviour more closely to pinpoint the causes of this difference in breakdown behaviour. Such an understanding will likely alleviate problems in the traditional approach, which is indeed more desirable in distributed estimation configurations.
  - **Improved estimation of the line of sight (LOS) delay:**
    In simple approaches, the LOS delay is estimated as the starting point of the channel impulse response. Such an approach, however, is biased due to the temporal spreading by the pulse shaping filter. Proper delay estimation taking into account the pulse shape is in turn sensitive to closely spaced secondary path delays. We intend to investigate improved estimation approaches for the LOS delay. Furthermore, many existing approaches are based on an instantaneous channel estimate. This means that delay estimation becomes quite ill-conditioned when the corresponding channel taps pass through a deep fade. In order to improve the delay estimation, it should be based on a combination of instantaneous channel information and power delay profile information. The proper combining of these two noisy (estimated) sources of information will also be investigated.
- ETH (26)
  - **Seamless handoff algorithms for WLANs:**
    Existing WLAN technologies (e.g., IEEE 802.11) only allow break-before-make handover. We investigate seamless handoff strategies in WLANs to meet QoS constraints of real time services.

5 Newcom Department 1 Participants: Technical Expertise and People

This section details which partners contribute to the activities of Department 1, the technical expertise that each brings, and the people who compose each partner.

1 **ISMB**

Technical expertise:
Coding and decoding for Short Block Lengths.

People:
Libero Dinoi has been involved mainly in the design of interleavers for turbo codes and now, together with Francesco Sottile, is working on the development of LDPC codes design algorithms.

2 **NKUA**

Technical expertise:
Synchronization in OFDM systems; MIMO systems; Adaptive coding and modulation; Multi-carrier systems.

People:
Yiannis Dagres <jdagres@phys.uoa.gr>
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Konstantinos Nikitopoulos <cnikit@cc.uoa.gr>

4 **Intracom**

Technical expertise:
Adaptive modulation; Adaptive coding; OFDM; Turbo coding and decoding; Diversity techniques.

People:
Researcher: Panagiotis Dallas <pdal@intracom.gr>
PhD Student: Emmanouil Kalantzis <ekal@intracom.gr>

5 **TECHNION**

Technical expertise:
MIMO systems; Iterative (turbo) receivers; Multiuser detection

People:
Researchers: Shlomo Shamai, Yonina Eldar, Yossi Steinberg, Shraga Bross, Moshe Sidi, Igal Sason.

Doctoral students: Aminadav Weisel, Michael Katz, Amichai Sandrovitch, Chanan Weingarten, Ilan Shuskover, Aran Bergman, Oren Somekh, Moshe Salhov, Gil Weichman.

6 **Bilkent:**

Technical Competence: Information theory and coding; iterative coding and decoding; short block coding; OFDM and MIMO systems; Wide-band signaling; Multiuser decoding; Multiuser detection.

People: Researcher: Erdal Arikan <arikan@ee.bilkent.edu.tr>
Ph.D. student: Ahmet Serdar Tan

7 **ISIK**

Technical expertise: OFDM and MIMO systems; Bandwidth efficient coding; Synchronization; Multicarrier systems; Blind receivers; Parameter estimation; Advanced signal processing techniques for wireless communications systems.

People:
Dr. Erdal Panayırcı <eepanay@isikun.edu.tr>
Dr. Hakan Cirpan <hcirpan@istanbul.edu.tr>

Dr. Umit Aygolu <aygolu@ehb.itu.edu.tr>
plus 4 Ph.D. students.

8 UPC

Technical expertise:
∗ Adaptive Coding and Modulation: Ana Pérez-Neira, Antonio Pascual, Antoni Morell;
∗ MIMO Signaling: Ana Pérez-Neira, Antonio Pascual, Antoni Morell;
∗ Mobility tracking: Montse Nájar

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9 CTTC

Techincal expertise:
∗ OFDM: Carlos Bader, Stephan Pfletschinger
∗ MIMO systems: Xavier Mestre, Mònica Navarro, Antonio Mollfulleda
∗ Multi-carrier systems: Carlos Bader, Stephan Pfletschinger
∗ Iterative (turbo) receivers: Mònica Navarro, Stephan Pfletschinger
∗ Multiuser decoding: Mònica Navarro, Stephan Pfletschinger
∗ MIMO signaling: Diego Bartolomé, Xavier Mestre, Carles Anton

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10 UPF

Technical expertise:
Short block coding; MIMO systems; Iterative (turbo) receivers.

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17 GET

Technical expertise:
Short block coding; OFDM and MIMO systems; Wide-band signaling; Adaptive coding and modulation; Bandwidth efficient coding; Synchronisation; Multi-carrier systems; Blind receivers; Iterative (turbo) receivers; Parameter estimation; Multiuser decoding; Multiuser detection.

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18 Supélec

Technical expertise:
Coding and modulation for MIMO systems; Signalling schemes for wide-band regime; Adaptive coding and modulation; Synchronisation, channel estimation, and equalization algorithms in low signal to noise ratios; Receiver designs for Multi-carrier systems; Receiver designs for MIMO systems; Blind receivers; Parameter estimation in iterative receivers; Multiuser detectors for advanced applications.

People:
Researchers: Hikmet Sari, Jacques Palicot, Armelle Wautier, Walid Hachem, Antoine Berthet, Yves Louet, Pascal Bianchi, Lionel Husson
Ph.D. students: Florence Nadal, Serdar Sezginer, Sophie Gault, Clemence Alasseur, Frédérique Sainte Agathe

19 CNRS

Technical Expertise:
Synchronisation; Multi-carrier systems; MIMO systems; Blind receivers; Iterative (turbo) receivers; Parameter estimation; Multiuser detection; Mobility tracking.

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21 **France Telecom**

Technical Expertise:
Short block coding; OFDM and MIMO systems; Wide-band signaling; Synchronisation; Multi-carrier systems; Iterative (turbo) receivers; Multiuser decoding.

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22 **Eurécom**

Technical expertise:
Short block coding; MIMO systems; Multi-carrier systems; Blind receivers; Iterative (turbo) receivers; Parameter estimation; Multiuser decoding; Multiuser detection.

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24 **VUT**

Technical expertise:
∗ OFDM, Multi-carrier systems, Channel estimation and equalization (Matz, Hlawatsch, Hartmann, Schfhuber)
∗ ST coding, MIMO detection algorithms (HLawatsch, Weinrichter, Seethaler, Gritsch, Badic)
∗ Wide-band signaling (Schafhuber, Matz, Hartmann)
∗ Parameter estimation (Matz, Hlawatsch)
∗ Multiuser detection (Hlawatsch, Seethaler)

People:
Researchers: Gerald Matz, Franz Hlawatsch, Johann Weinrichter, Dieter Schafhuber
PhD Students: Manfred Hartmann, Dominik Seethaler, Gerard Gritsch, Biljana Badic

26 **ETH**

Technical expertise:
Short block coding; OFDM and MIMO systems; Wide-band signaling; Adaptive coding and modulation; Synchronisation; Multi-carrier systems; Parameter estimation; Network signalling.

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28 **LNT-TUM**

Techical expertise:
Iterative (turbo) receivers; Parameter estimation.

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29 **TUA**

Technical expertise:
Joint Iterative Synchronization and Decoding; Wideband System Scalability; Coded OFDM; Ultra-wideband Systems.

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30 **UEN**

Technical expertise:
Short block coding; MIMO systems; Bandwidth efficient coding; Synchronisation; Iterative (turbo) receivers; Multiuser decoding; Multiuser detection.

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31 **DLR**

Technical expertise:
OFDM and MIMO systems; Adaptive coding and modulation; Bandwidth efficient coding; Multi-carrier systems; Parameter estimation; Multiuser decoding; Multiuser detection; cellular aspects.

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32 CNIT

Technical expertise:
(i) Multi carrier CDMA and OFDM; (ii) space-time channel estimation; (iii) channel equalization in time and frequency; (iv) bit and power loading; (v) signal processing for MIMO systems; (vi) location/tracking of mobile terminals.

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Osvaldo Simeone [ii,v]
Roberto Bosisio
Matteo Albanese [iii]
Enrico Paolini

34 FTW

Technical expertise and people:
Short block coding (Jossy Sayir), OFDM (Thomas Zemen, Tomas Nordström, Rickard Nilsson, Georg Tauböck), MIMO systems (Ralf Müller, Christoph Mecklenbräuker, Laura Cottatellucci, Georg Tauböck), Wideband signalling (Christoph Mecklenbräuker), Synchronisation (Christoph Mecklenbräuker), Multi-carrier systems (Thomas Zemen, Ralf Müller, Christoph Mecklenbräuker), Iterative (turbo) receivers (Gottfried Lechner, Jossy Sayir, Ralf Müller, Joachim Wehinger), Parameter estimation (Christoph Mecklenbräuker, Thomas Zemen), Multiuser decoding (Ralf Müller), Multiuser detection (Laura Cottatellucci, Ralf Müller), MIMO capacity (Ralf Müller, Laura Cottatellucci)

36 PUT

Technical expertise:
OFDM; Adaptive coding and modulation; Synchronisation; Multi-carrier systems.

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37 UGent

Technical expertise:
Synchronisation; Multi-carrier systems; MIMO systems; Multiuser decoding.

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38 UCL

Technical expertise::
Synchronisation; Multi-carrier systems; MIMO systems; Iterative (turbo) receivers; Multiuser decoding; Multiuser detection.

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40 ESA

Technical expertise:
Short block coding; Adaptive coding and modulation.

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Catherine Morlet <catherine.morlet@esa.int>

41 **AAU**

Technical expertise:
Iterative signal and information processing; joint multiuser detection and channel estimation; MIMO systems.

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42 **Chalmers**

Technical expertise and people:
Adaptive modulation and coding:
Tony Ottosson, Arne Svensson

OFDM: hardware concerns:
Thomas Eriksson

CDMA: multiuser detection, synchronization, parameter estimation:
Erik Ström, Tony Ottosson, Arne Svensson

OFDM-CDMA: hybrid general design and coding for multiuser ODFM-CDMA:
Erik Ström, Tony Ottosson

Convolutional codes:
Tony Ottosson

Source coding: speech and audio coding, vector quantization:
Thomas Eriksson, Erik Agrell

CPM:
Arne Svensson

45 **LU**

People and technical expertise:

Rolf Johannesson <rolf@it.lth.se>: Error correction coding; iterative decoding.
John B. Anderson <anderson@it.lth.se>: Coded modulation, bandwidth efficient coding.
Ove Edfors <oes@es.lth.se>: OFDM, iterative decoding, MIMO.

48 **NTNU**

Technical expertise:
OFDM and MIMO systems; Adaptive coding and modulation; Multi-carrier systems; joint source-channel coding; wireless channel estimation and prediction; multiuser scheduling algorithms; equalization and synchronization; diversity; information compression; digital filtering; multirate systems; ad hoc networks; receiver structures; hardware implementation issues.

People:
Researchers: Geir Øien, Nils Holte, Tor A. Ramstad, Kjell J. Hole, Lars Lundheim

Ph.D. students: Bengt Holter, Ola Jetlund, Anna Kim, Greg H. Håckonsen, Fredrik Hekland, Duc Van Duong, Lin Gang

49 UiB

Technical expertise and people:
Short block coding: Rate compatible turbo codes of moderate lengths.
Professor Øyvind Ytrehus, Postdoc Eirik Rosnes

Short block coding: Effects of pseudocodewords in LDPC and turbo codes of moderate length.
Professor Øyvind Ytrehus, Postdoc Eirik Rosnes, PhD Students Pål Ellingsen and Susanna Spinsante

Short block coding: Adaptive coding and modulation
Professor Øyvind Ytrehus, Postdoc Eirik Rosnes, Professor Kjell J. Hole

Short block coding: Bandwidth efficient coding
Professor Øyvind Ytrehus, Postdoc Eirik Rosnes

Short block coding: ARQ systems
Professor Torleiv Kløve, PhD Student Irina Gancheva

Parameter estimation
Postdoc Eirik Rosnes

Signal design for OFDM
Professor Tor Helleseth, Postdoc Matthew G. Parker

Dirty paper coding
Professor Øyvind Ytrehus, Postdoc Hans G. Schaathun, Visiting Professor Ángela Barbero

51 UoSo

Technical expertise:
OFDM; adaptive coding and modulation; single- and multi-carrier CDMA systems; blind receivers; MIMO system; Multi-user detection; channel coding and coded modulation; narrow and wideband beamforming; turbo transceivers; minimum bit error ratiotransceivers.

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53 UoE

Technical expertise:
OFDM and MIMO systems; Wide-band signaling; Synchronisation; Multi-carrier systems.

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Prof Bernie Mulgrew <Bernie@ee.ed.ac.uk>
Dr John Thompson <jst@ee.ed.ac.uk>
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58 **KTH**

Technical expertise:
Channel state information and capacity limits; multi-user systems; MIMO systems; space-time codes; code design for joint equalization and decoding.

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61 **UoY**

Techhnical expertise:
Iterative (turbo) techniques; Channel estimation and synchronisation; MIMO transmission techniques; WCDMA systems including multi-user detection; MIMO OFDM systems; Cellular MIMO systems.

People:
Alister G. Burr (all the above, at least in outline) <alister@ohm.york.ac.uk>
Yuriy Zakharov (Estimation and synchronisation techniques, WCDMA)
George White (WCDMA, turbo-codes)
Lingyang Song (Space-time codes)
Yu Zhang (MIMO OFDM systems)
Zhuo Wu (Cellular MIMO systems)

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[‡] For detailed contents please refer to http://www-mobile.ecs.soton.ac.uk ; ISBN 0-471-15039-8.

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