Newcom (E.C. Contract no. 507325)
Department 1
Signal Processing at Large in Wireless Networks
Identifying "Knowledge Gaps"

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1 Introduction

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 cooperative 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 coordinate 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.

1.1 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 symbols 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., [16]) 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): 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): 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): 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): 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): 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): 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 informaation bits). While the non-binary LDPC codes have to be regular to reach good performance, the optimization of these codes is focused on the choice of the non-binary values in the parity matrix and constructions of matrices that minimize the number of small cycles.

- CNIT (32): 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): Development of analytical methods to compute and bound EXIT functions for linear codes in order to analyze the convergence behavior of iterative decoders. The recently introduced concept of bounding the combination of mutual information values [34] lead to bounds on information transfer functions for repetition codes, single parity-check codes, and applications to LDPC codes [58], [33]. The investigations focus on further generalizations 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-Nuernberg, Germany (there have already been collaborations) and Prof. Shlomo Shamai of Technion, Israel.

- UoB (49): Investigation of rate compatible turbo codes of moderate lengths. Further we have as a project to investigate the effect of pseudocodewords, especially in LDPC codes, and decoding algorithms that are not or less affected by pseudocodewords, similar to the work carried out at ISMB (01).

1.2 Signal Design for OFDM and MIMO Systems

The great flexibility of OFDM explains its increasing deployment in recent years, in collaboration with the increased theoretical capacity of multi-antenna (or MIMO) systems. The increasing demands on 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 (see also Section 1.9); (iii) peak-to-average power ratio optimization 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 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.

1.2.1 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 during FFT (or IFFT) calculations due to limited quantization levels, rounding and truncation, and behaves as an additional degradation beyond nonlinear distortion caused by power amplifiers. Tests show that the bit error rate degradation in OFDM transmission induced by nonlinear distortion may not be the key factor after all which characterises 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, 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 quantization noise, while setting it too low induces excessive clipping distortion.

A few methods for peak-to-average power reduction in OFDM systems have been elaborated. For the most part, they involve various combinations of coding, windowing, and reference signal subtraction, in addition to some complicated signal manipulations, which in turn require transmitting some overhead information. Suitable codes favoring small small peak-to-average power ratios include Golay codes and generalized 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 the 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 behavior 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 linearization 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): Investigate appropriate (spreading) code families for frame synchronization and multi-user detection in a MC-CDMA system, with special emphasis on the uplink transmission mode. Methods for reducing the peak-average ratio will be analysed and compared.

- VUT (24): 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 utilize up-to-date channel state information by compensating round-trip delays via channel prediction.

- UEN (30): Design and investigation of PAR reduction schemes based on lattice-reduction-aided precoding techniques [66] and the application of a sphere decoder for arbitrary signal constellations and FFT sizes. A suited decoding metric is to be designed, and low-complexity versions similar to selected mapping and partial transmit sequences techniques [41] will be developed.

- CNIT(32): 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.

- PUT (36): 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, minimization of transmission overhead caused by side information, as well as on noticeable system performance improvement.

- NTNU (48): Investigation of the influence of PAPR on required complexity/cost of A/D converters and FFT processing in OFDM receivers.

1.2.2 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 traditionally 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 capitalize on the knowledge of the propagation features must be addressed.

Partial channel state information situations have been far less explored, and the relationship between the quality and degree of channel state information and the associated capacity-achieving architecture needs to be further studied, presenting 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.

Especially, for time-variant multiple-access MIMO channels the exploitation of the propagation characteristics become even more important. Channel estimation methods like the Kalman [30] or Wiener filter [53] 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-Loeve transform [54, 55].

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 [64] that the spatial stationarity of the channel is below 100 wavelengths. Measurements at 5.2GHz have also shown that the Jakes model, although frequently used for analysis and simulations, is a rather crude idealization of real scattering environments [72].

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 [52]. The Fourier basis expansion, however, suffers from a high estimation bias due to spectral leakage and Gibbs phenomenon. We conclude here that the channel subspace is not accurately spanned by a truncated Fourier basis [71].

We note that transmitted data blocks are of finite duration. Using results from the theory of bandlimited and time-concentrated sequences, it has been shown that discrete prolate spheroidal sequences span the channel subspace for time-variant channel estimation [71] per subcarrier in an OFDM based system. This subspace representation is termed the Slepian basis expansion. A dual situation exists in the frequency domain [17], so that a modified Slepian basis expansion can be applied for exploiting the correlation between the individual subcarriers [26].

A straightforward application of time-variant SISO estimators to all elements of the MIMO matrix is inefficient. We need 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-variant 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):
  - 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 quantization 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.

– 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 wireless systems where the design of the feed-back channel (TDD or FDD) is taken into account in the overall multiuser system performance. Uncoded analgog linear modulation is an effective way to transfer CSI from autonomous terminals to a basestation 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): Analysis and development of optimal MIMO architectures for situations with partial channel state information at the transmitter. Design of scalable signal processing MIMO pre-coding 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.

- VUT (24): 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 utilize up-to-date channel state information by compensating round-trip delays via channel prediction.

- ETH (26): We investigate the impact of varying degrees of channel knowledge on wideband multiantenna 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. We investigate the impact of varying degrees of channel knowledge on wideband multiantenna 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): 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): 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): 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): Further investigation of the impact of imperfect and/or outdated channel state information on the performance and design of OFDM and MIMO systems that utilize pilot-aided link adaptation (adaptive coded modulation). In a slightly more long-term perspective, similar investigation for opportunistic multiuser scheduling algorithms in such systems. Optimization 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 optimization 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 multiuser scheduling algorithms.

- UoSo (51): The family of minimum bit error rate (MBER) multiuser 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 minimizing 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 [23]. Initial results [2] indicate that the MBER MUD is capable of supporting more users than the number of receiver antennas available, while outperforming the MMSE MUD.

  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 utilizes the antenna array elements more intelligently, than the standard minimum mean square error (MMSE) approach [7]. Consequently, MBER beamforming is capable of providing significant performance gains in terms of a reduced bit error rate (BER) 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 priciples 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 [8, 9, 51].

1.2.3 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 recognize 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 the receiver design permit blind or non-blind acquisition and estimation of various parameters, such us channel parameters and modulated data (cf. Section 1.8).

The "knowledge gaps" in this area include 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 PSP-based algorithms.

Action Plan

- GET (17):
  - 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.
  - A contribution for developping 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): 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 Cramer-Rao bounds) and analytic performance measures (mean and standard deviation).

1.2.4 Pulse Shape Design

Conventional OFDM systems use a rectangular waveform in the time domain that leads, with a sinc-impulse, to a bad localization in the frequency domain. Furthermore, in a practical setup this rectangular pulse has to be extended by the 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 deign 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 an appropriate windowing. But in a standard OFDM setup, in order to remove the resulting inter symbol interference, this leads either to the need of a post-processing equalizer [39], [38] or to the addition of an extra guard interval [47]. Another windowing technique leading to good frequency localization 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 [25], [37]. The gap to fill in this context is to design perfectly orthogonal systems with rational oversampling factors being as close as possible to 1 [48] 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 [4] 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 regard to an appropriate time-frequency localization 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 [57], though, nearly optimal results can be obtained with very short waveforms.

A theoretical analysis [32] 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 generalizations of OFDM/Offset-QAM have already been investigated [56], [4] 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 equalizer, 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): Analysis and design of short waveforms taking into account the peak-to-average-power-ratio criterion for different types of multicarier systems. Practical evaluation of these systems for transmission over mobile radio channels.

- VUT (24): Development of pulse shape design and optimization algorithms for OFDM/BFDM 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 synchronization errors. Furthermore we aim to develop advanced OFDM/BFDM pulse optimization algorithms to achieve further performance enhancements.

- NTNU(48): Optimization 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.

1.3 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 sizable knowledge gap surrounds space-frequency code design, where both spatial and frequency diversity are jointly exploited. Although design criteria are readily devised [59], 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 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 MIMO will outperform receive antenna diversity [5]. When there are more antennas at the receiver than at the transmitter, interference suppression can be performed. As a result, when a channel is poor, receive antenna diversity will outperform MIMO, with MIMO giving higher capacities when the channel is good [14]. 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 and coding is 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 [15]. Using multiple antennas will also tend to decrease the channel diversity, decreasing the multiuser diversity gains. Therefore, considering the interaction between scheduling methods and multiple antenna 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 ususally 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 "cooperative 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 unchartered 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):

  - Space-Time Code (STC) design has been mainly based on the pioneering work presented by V.Tarokh *et al.* [59] where design principles were first established. Our first action will be to define a common framework under which one can fairly characterize 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.
  - 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 [12] coding techniques: these techniques are now very well recognized, 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 cooperation 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 endeavor, with whom contacts have been established are: Prof. Helmut Bölcskei of ETH, and Prof. Giuseppe Caire of Eurécom.

- UPC (8): Development of multiuser 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 multiuser robust schemes trying to incorporate recent research into robust point-to-point MIMO systems against limited channel knowledge.

- 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 correlations in order to reduce computational complexity.

- ETH (26): 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.

- DLR (31): Differential modulation/demodulation suffers from a decorrelation of the channel. Such a decorrelation is achieved by cyclic delay diversity (CDD) [13], 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.

- KTH (58): 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.

1.4 Large-scale multi-user and multi-antenna system analysis

The theory of large random matrices is now recognized 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 modeled 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 realizations ([62], [63]). 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 correlations between transmit and/or receive antennas, line of sight components, in additional to frequency and/or time selectivity ([11]).

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): We propose to analyze 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 analyze the finite-sample size limitations of typical signal processing architectures for communications such as channel estimation or spatial filtering schemes.

- Supelec (18):

  – A contribution for writing a mathematical state-of-the-art document. The available methods used to describe the behavior of different random matrix models in the asymptotic regime will be presented in this document.

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

- CNRS (19) + FTW (34):

  - 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 Ricean 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 Ricean channels and/or frequency selective is less well understood. We therefore plan to study the capacity of large MIMO systems in this context.

- 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;
  - 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 optimize 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.

1.5 Wideband Network Scalability

The initially touted features of CDMA systems, which spread transmitted signals over a larger frequency band, have recently encountered information-theoretic proofs of their limited scalability to future wideband systems. This casts serious doubt on the usability of CDMA—the design choice for 3G systems—for systems beyond 3G. Instead, peaky signaling schemes, which concentrate the signal power in both time and frequency, can attain channel capacity. Present knowledge gaps include (i) coherent design methodologies for scalable signal sets; and (ii) optimal detection strategies adapted to peaky signals over wideband multipath channels.

Indeed, recent work [40], [60] shows that large bandwidths over fading multipath channels cannot be used effectively by systems that spread the transmitted signal power uniformly over both time and frequency. By contrast, peaky signalling schemes that concentrate the signal power in both time and frequency achieve 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 reliable estimation of the required set of channel parameters requires algorithmic complexity that grows much faster than the available bandwidth. This is particularly relevant for the design of wireless systems beyond 3G because it casts a doubt on the feasibility of wideband CDMA in meeting future system requirements.

The objective of this research activity will be to investigate the scalability of various signalling schemes, in particular W-CDMA, under tractable models representative of future wireless systems. The success of this work will be measured by the insight we gain into (i) how to design scalable signal sets; and (ii) reaching a better understanding of the fundamental trade-offs in using pilot signals vs. combined channel estimation and detection. A subtopic of this research effort will be the study of the same type of problems when multiple antennas are used at the transmitter and/or receiver.

In this direction, we may note that 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) [10], [70], [65]. 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 confronts a fundamental compromise between a low re-use distance which requires fewer frequency band, 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. Successful lines of attack require expertise in information theory, coding and modulation, network topology and radio resource management.

Action Plan

- Bilkent (06): Since a great deal of theoretical work has already been done on wideband scaling of signalling schemes, our initial work in the first six months has been to focus on the applicability and implications of these results for the UWB schemes currently under study for IEEE 802.15.3a personal area network physical layer standardization. In [3], we give estimates on the achievable rates for such networks using a channel model specified by the same IEEE group [6]. 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 [19]; i.e., the signal power is permitted to grow in proportion to the utilized bandwidth. As a result of this relaxed constraint on transmitter power, it turns out—not surprisingly—that there exist signaling schemes for UWB channels that are not peaky and that scale well with bandwidth. Another conclusion in [3] is that under the target operating conditions for UWB channels, relatively quick estimation of the channel state is possible, suggesting the use of feedback schemes for better channel utilization.

- 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, ...).

- TUA (29): 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 analyzing 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): 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; optimization 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.

1.6 Multi-bit per Hertz coding

The celebrated Shannon theory predicts reliable communication 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 signaling rates above 1 bit/s per Hertz of channel bandwidth, namely trellis-coded modulation and coset codes, multilevel codes and bit-interleaved coded modulation.

Recently, novel promising methods based on discrete-time real-number convolution, on linear congruential trellis label generation, and on severe filtering followed by a near-optimal reduced-search decoders have been developed. Such methods constitute potential contenders for coding schemes that adapt rapidly to changing channel conditions, featuring the ability to change rate easily and especially change to very high rates. Little theoretical structure exists, however, for coding at very flexible rates (from zero to very high rates), and so investigation in this direction is another priority.

A major problem in coding for very high order modulations (64-QAM or above) is the fact powerful codes such as turbo-codes and/or LDPC codes are generally designed in a binary field, leading to performance degradation caused by the demapping step at the receiver. Treillis-coded modulations have shown the importance of designing codes directly in the constellation space, in order to achive very good performance. This is even more important when the codeword length is relatively small (less than 2000 bits).

The knowledge gaps here therefore include (i) whether spectral efficiencies of 2–8 bits/s/Hz are achievable at tolerable error rates; and (ii) 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.

Another well indentified knowledge gap is then to design powerful pseudo-random codes in high order Galois fields. The field order must be equal 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.

Action Plan

- GET (17): 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 the binary version and they open new possibilities for optimizing 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 the one proposed in Section 1.1

- CNRS (19): We will study the performance of non-binary LDPC codes on high order modulation (up to 256-QAM), when the LDPC code is build in a Galois field with same (or greater) order than the constellation. This ensures that all mappings of the constellation perform equally, which reduces the optimization 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): Application of numerical optimization schemes to find suitable bit-mappings for QAM- and PSK-modulation employed in bit-interleaved coded modulation with iterative decoding (BICM-ID). Analysis of the gains in transmission power for BICM-ID schemes employing convolutional and Turbo/LDPC channel codes.

- CNIT (32): 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): Space-Time Block Coded Inphase-Quadrature phase (IQ)-interleaved Trellis Coded Modulation (TCM) and Turbo TCM (TTCM) schemes were proposed in [42], 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 non-dispersive 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.

- UoE (53): Development of numerical optimization methods for the design of bit-mappings employed in iterative decoding/demapping schemes at the receiver. Performance and complexity analysis of the optimization methods.

1.7 Joint (Turbo) Receiver Optimization

Traditional receiver design involves separate algorithms for synchronization, equalization, and decoding. The success of turbo decoding and related techniques has inspired joint iterative algorithms linking all receiver components so that imperfections in one stage can be compensated by another. This also favors reduced complexity circuit design by combining tasks on a single chip. Initial experimental evidence is promising, albeit heuristic, and major shortcomings are presently observed.

To understand the basis of this problem setting, we may note that the exchange of soft information between distinct receiver components results in iterative algorithms which, if convergent, result in a state of “consensus” concerning the information components of a signal. These methods are known to yield only approximate maximum likelihood solutions, owing to the presence of loops in their equivalent belief propagation graphs. Present understanding thus only partially explains the success of “turbo” methods, and the adaptation of information theory tools to describe such iterative algorithms is thus fundamental to the successful design of interconnected receiver components. Without such knowledge, design principles remain heuristic and open to scrutiny and debate.

To complicate matters, performance improvements of such turbo algorithms are quite manifest in some circumstances, but misconvergence behavior such as limit cycles, chaos, or numerical singularities are also observed in harsher communication environments. Simulation evidence [50] shows that a good first estimate (or a priori information) has a critical impact on the performance of such iterative algorithms, unlike classical turbo decoding algorithms where little a priori knowledge is necessary to start the snowball rolling. This reinforces the need for estimating channel state information in a number of iterative/turbo schemes, including the channel impulse response in turbo-equalization, or phase or frequency offsets in turbo-synchronisation. An promising approach to turbo-processing with partial CSI uses the EM algorithm for parameter re-estimation (e.g., [31]), which relates further to the advanced signal processing techniques of Section 1.8.

Key knowledge gaps which impede present-day deployment therefore include: (i) convergence proofs and/or stability analyses of the "turbo principle" once distinct receiver subsections are combined; (ii) data-efficient estimators for initial conditions ensuring that the "turbo effect" is triggered; and (iii) robustness to partial channel state information and embedding of re-estimated channel state parameters in the turbo-processor.

A useful starting point in this direction is to examine the interaction between synchronization and channel equalization, 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 should help guide the design of more sophisticated and robust joint channel estimation and synchronization algorithms, which may employ iterative synchronization/equalization algorithms appealing to the turbo principle. Indeed, algorithm design thus far has assumed perfect channel state information. Some studies (e.g., [61], [18]) have modified the outer processor when only partial channel state information is available. Design of optimal outer processors (in a maximum likelihood sense) is desired and sub-optimal versions should be derived with a better understanding of the approximations.

Extensions to more advanced configurations, 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. A promising approach in this direction revolves around information geometry [28] which lends valuable geometric insights inbto these iterative algorithms, and which can also be exploited to accelerate the convergence rate.

Action Plan

- GET (17): Development of information geometry description of iterative receivers, which do not necessairly appeal to asymptotic large sale system results. Aim to isolate which signal-plus-interference-to-noise ratios, and which initial conditions, lead to a convergent system.

- CNRS (19): Synchronization and iterative decoding can be achieved jointly using novel turbo synchronization schemes estimating iteratively the carrier phase and the received data. This turbo receiver structure will be based on block turbo codes. Performance at low SNR will be investigated. In addition, a study the robustness to imperfect channel state information will be undertaken, aiming to detect the key elements: influence of SNR in triggering the turbo-processor, as well as the impact on the number of iterations. Development of new algorithms with a modified outer processor to identify performance limits and required initial conditions.

- VUT (24): Development of efficient hard and soft decoding algorithms for large linear data models with high-order modulation. The goal is to develop close-to optimum algorithms with reduced complexity and to study their impact on iterative receiver processing. We further plan to work on the information geometric analysis and acceleration of iterative receiver structures.

- TUA (29): The employment of iterative decoding schemes results in very power efficient transmission and is therefore well suited for scenarios with low signal-to-noise ratio (SNR). On the other hand, frequency and carrier synchronization is challenging in scenarios with low SNR. However, iterative decoding techniques require accurate synchronization to fully exploit their capabilities. Especially in packet based transmission schemes with short data packages the introduction of pilot symbols is limited in order to not significantly decrease the useful data rate. Hence, we plan to develop optimal iterative joint carrier synchronization and decoding algorithms to also use the energy contained within the data packages for the task of synchronization and to minimize the pilot symbol overhead.

- DLR (31): Iterative receiver structures with different modulation schemes and an a posteriori probability (APP) greater than a specific threshold outperform conventional modulation schemes. The new schemes will be investigated in coded MC-CDMA systems. To improve the performance of iterative receivers under realistic channel conditions, channel estimation is included into the iterative receiver structure. Iterative channel estimation benefits from the additional knowledge of hard- or soft-decided symbols from the decoder. Iterative channel estimation algorithms will be investigated for coded MC-CDMA systems with respect to performance and robustness.

- FTW (34): Extend convergence analyses of iterative multiuser decoding in systems with many users to include channel estimation in the iterative loop.

- CNIT (32): Turbo decoding and turbo equalization 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 equalizer-decoder algorithm which operates mainly in the frequency domain.

- PUT (36):

  – Development of new structures of carrier phase synchronization 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.

  – Studies of new iterative equalization 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, reasearch on joint channel estimation and turbo-equalization will be conducted, as well as the analysis of turbo-equalization for higher order modulations.

- UCL (37) and UGent (38): Turbo synchronisation and parameter estimation, focusing on carrier phase and timing recovery for soft-input-soft-output systems, as well as CIR/noise estimation for CDMA and MIMO coded systems. Convergence issues will be studied in the light of belief propagation and factor graphs.

- AAU (41): Advanced iterative receivers for joint multiuser 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): We have in the past designed iterative schemes for channel estimation, synchronization, and channel decoding (turbo codes, convolutional codes, Hadamard codes). We want to set these and similar schemes on a more solid theoretical basis by formalizing 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)–(iii) outlined above. Clearly, this study also touches the knowledge gaps described in Section 1.8 Advanced Signal Processing Algorithms for Wireless Communications.

- UoSo (51): Joint source-coding, channel-coding and modulation schemes based on Variable Length Codes (VLCs), Inphase-Quadrature phase (IQ)-interleaved Trellis Coded Modulation (TCM) and Turbo TCM (TTCM) schemes are proposed [23]. A significant coding gain and a lower error floor are achieved without bandwidth expansion. Further research has to address the employment of such schemes in the context of dispersive wideband channels.

  Joint video-coding, channel-coding and modulation schemes based on a Constant Bit Rate (CBR) video codecs, Variable Length Codes (VLCs) as well as Trellis Coded Modulation (TCM) and Turbo TCM (TTCM) schemes were proposed in [**?**]. These arrangements have a latency of a single video frame duration. A significant coding gain may be achieved without bandwidth expansion with the advent of iterative decoding exchanging extrinsic information between the VLC and the TCM or TTCM decoders. However, further research is required in rendering such sophisticated turbo transceivers applicable to wideband channels, which currently constitutes a knowledge gap.

  A reduced complexity turbo detection scheme [22] referred to here as the R-TD arrangement, is proposed for employment in space-time trellis coded (STTC) systems using the in-phase/quadrature-phase (I/Q) cancellation technique previously developed for single-transmitter and single-receiver systems. The R-TD scheme decomposes the received signal into its constituent I and Q signal components and detects these components separately, hence reducing the number of possible signal combinations to be 'tested' by the detector.

A recently proposed space-time signal construction method that combines orthogonal design with sphere packing, referred to here as STBC-SP, has shown useful performance improvements over Alamouti's conventional orthogonal design [1]. In recent years, iterative decoding algorithms have attained substantial performance improvements in the context of wireless communication systems. In this paper, we demonstrate that the performance of STBC-SP systems can be further improved by concatenating sphere packing aided modulation with channel coding and performing demapping as well as channel decoding iteratively.

1.8 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-maximization algorithm;
- The SAGE algorithm;
- The Baum-Welch algorithm;
- Per-Survivor processing;
- Kalman filters and their extensions;
- Hidden Markov modeling;
- Sequential Monte Carlo filters;
- Stochastic approximation algorithms;
- Sphere decoding and convex relaxation techniques (semidefinite relaxations) 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, synchronization, equalization 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 equalization, interference suppression for multiple access channels and tracking of time varying channels, the problem of jointly combatting 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 normalizing constant. So far two basic types of algorithms, the Metropolis algorithm and the Gibss 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

- Technion (05): Multiuser receivers for detection of code-division multiple-access (CDMA) signals try to mitigate the effect of the multiple-access interference (MAI) and the background noise. Recent developments in optimization theory has lead to an intensive search for advanced signal processing techniques for multiuser detection. 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 our research, we plan to investigate new robust detection algorithms including linear detectors, suboptimal relaxations of the optimal ML detectors, and optimal detection schemes. For each of these we plan 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 Boelcskei 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 characterization 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-Loeve (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 characterize 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 equalization 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 equalization 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, synchronization, equalization 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):
  - 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 modeling these errors and exploiting the capabilities provided by convex optimization theory.
  - Advanced algorithms for the joint design of several transmitters and receivers having multiple antennas in a multiuser scenario. Resolution of the joint optimizaton problem using heuristic techniques such as simulated annealing.

- ETH (26):
  - Sphere Decoding: Sphere decoding has been identified as a promising means to perform maximum likelihood (ML) detection in MIMO oder multiuser 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 Equalization: Computational demands for MIMO OFDM increase with the number of tones and drastically with the number of antennas. Current algorithms

for channel equalization 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 equalization for MIMO OFDM.

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

- DLR (31): 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) optimization will be derived and extended.

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

- AAU (41): 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 [**?**]. 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): 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 [46] 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.

  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 [45], it is of high interest to develop wireless MIMO transceivers that are capable of approaching these capacity estimates.

Novel multiuser 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 optimization 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 [67, 24].

A spatial diversity reception assisted multiuser CDMA detectors based on genetic algorithms (GAs) are more sophisticated than their counterparts dispensing with diversity reception. In [68] 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 multiuser 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 multiuser 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 multiuser 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 multiuser 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 multiuser detector is capable of achieving a near-optimum bit error rate performance, while imposing a lower complexity than the optimum multiuser detector [24, 69]. 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): Development of good quantisers for the soft-outputs processed in iterative decoding and multiuser detection schemes. Analysis of the trade-off between decoding performance and quantiser accuracy/memory requirements.
- KTH (58): 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.

1.9 Multi-User Codes

Present systems assign distinct/independent codes to multiple users, and regard other users as interference sources rather than peers. The only cooperative task between users concerns power control. Multi-access systems imposing user-level and network-level security (e.g.,"trusted" or "restricted" networks as opposed to open public networks) require bilateral authentication and leasing protocols, which may be viewed as a precursor to cooperative code assignment between users.

Wireless systems generally comprise multiple terminals or users that transmit to a central access point and vice versa. On the uplink, practical systems mostly employ multiple-access schemes that decompose the multiuser system into a set of parallel single-user links. This decomposition can be attained by assigning disjoint subsets of the available time interval (giving Time Division Multiple Access: TDMA) or the frequency band (giving Frequency Division Multiple Access: FDMA). Information-theoretic results [21] indicate that the overall sum capacity of the multiuser system exceeds the sum of the individual single-user capacities. Exploiting these multiuser capacity gains requires that all users collide in time and frequency. Full collision in turn calls for channel coding across all users which is significantly more demanding than channel coding for a single-user link. The design of good multiuser channel codes represents a largely unexplored field, presenting thus critical knowledge gaps.

Network coding is a recently proposed method that allows an increase in the achievable throughput when multicasting to a number of users. The basic idea is that intermediate nodes in a network are allowed not only to route but also to perform operations on the incoming data. Although the research is based on error-free transmission between the nodes, it is essential to consider the application of network coding for noisy channels, as are found in wireless networks. As information-theoretical results indicate that separate channel-network coding techniques do not guarantee optimal performance, on must consider the joint design of network coding and channel coding.

Random coding results for multiple-access channels with additive white Gaussian noise [20] reveal that the optimal coding strategy—i.e., either joint or single-user code design—is governed by the rates at which the users transmit. Although the users are not capable of cooperating, they can still be assigned jointly-designed codebooks. A critical knowledge gap for wireless applications is whether similar statements about the optimal coding strategy hold for wideband fading channels. Filling this knowledge gap would pave the way to the design criteria of codes for multiple users.

Future demands for higher data rates and improved link qualities call for the use of multiple antennas in wireless systems. The gains promised by MIMO techniques for point-to-point links carry over in an analogous fashion to multiuser systems [49]. The multiuser code design criteria mentioned above need to be generalized to account for the spatial dimension as well. A key knowledge gap here concerns how to design space-frequency codes for multiple-access channels; little work is available at present, yet the pay-offs in filling this gap would be immense in all multiuser wireless applications.

Of particular note are broadcast channels, motivated partly by Costa's "writing on dirty paper" [12], since the interference provoked by other users is known to the transmitter, suggesting how interference may be assimilated to side information for better efficiency at the receiver. This would result in greater complexity at the transmitter, in exchange for simpler design constraints at the receiver, of clear interest in commercial broadcast applications.

Action Plan

- CTTC (9): We propose to investigate bit allocation strategies optimized 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.

- ETH (26): The design of multiuser codes for wideband fading channels requires to characterize the conditions under which either single-user code design is sufficient or joint code design is necessary. We resort to cut-off rate as the performance criterion based on which the distinction between single-user and joint coding will be made. The analysis is conducted along the lines of [28] extending the results to wideband fading channels. The cut-off rate furthermore provides a viable means to derive the space-frequency multiuser code design criteria for finite block lengths, i.e. refraining from random coding arguments. The code design criteria in turn are expected to lead to profound insights into the design of practical coding schemes.

- DLR (31): 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 it has to be investigated, whether it is possible to benefit from the 'turbo-effect', when using more suitable modulation mappings.

- CNIT (32): 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 signaling 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 (LAS) CDMA known as LAS-CDMA and MC LAS DS-CDMA were shown to exhibit a 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 [44]. 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 multiuser detector. There are numerous related knowledge gaps in the design of such attractive codes exhibiting an IFW, amongst others the analytical 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-syncrhonous reception at the BS, despite the different propagation delays experienced by the different mobiles.

1.10 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 optimization 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 coordinate cell transitions and global ressource 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 dynamical 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 modeling of the shadow process which confounds mobility tracking.

Action Plan

- UPC (8):
  - 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 or beamforming configurations) offers increased potentialities in the task of locating a user equipment since better estimation of delays is obtained, and DOAs may be determined. New timing and angle estimation algorithms taking advantages of the use of smart antennas will be developed.
  - 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 solve the biased positioning estimation will be analysed, including high resolution estimation, Kalman filering, and other advanced techniques (cf. Sec. 1.8).

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