ASILUM: A PLATFORM TO EVALUATE ADVANCED COMBINATIONS OF SMART ANTENNAS AND MULTI-USER DETECTION FOR UMTS FDD AND TDD

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ABSTRACT

The purpose of this paper is to present and explain some results of ASILUM[1]*, a project included into IST (Information Society Technologies), a research programme of European Community. This project aims to contribute to the technical innovation and policies of the European Community by validating new transceivers concepts to increase the capacity of UMTS (FDD and TDD modes) through new and efficient interference mitigation schemes. These schemes are jointly using smart antennas and multi-user detection. They have been validated through link and system level simulations.*

1 Introduction

Self interference is a known problem in DS/CDMA systems, this will be especially true for 3GPP mobile radio systems that promise high data rates for multi-media applications. The problem is due to the fact that all users send in the same time and frequency band and that the same frequencies are used between all cells. DS/CDMA signals are separated by their individual code, however "conventional" receivers suffer from interference from the other users, as the codes are not orthogonal to each other. In the uplink the codes are not orthogonal to each other due to the unco-ordinated transmission from the different users with different multi-path profiles etc. This problem is minimized by the use of long pseudo random spreading codes which minimize the interference from one user onto another. In the downlink the users signals are transmitted in such a way that they are orthogonal to each other but due to multi-path effects the signals arrive at the terminals in a non-orthogonal way.

Interference in 3GPP systems will be more severe and more problematic than that experienced in 2G CDMA systems like IS-95 because of the utilization of different data rates by different users. High data rate users will generate a lot more interference than low data rate users, this means less users can be supported in such cells.

The interference not only limits the cell capacity but also the cell radius of the system. The cell radius is also very important to service providers as this determines the cost to cover a town or city. In early deployment of 3GPP, coverage is a lot more important than capacity and the benefit that interference cancellation and antenna arrays provides can mean that service providers are profitable sooner due to the lower start-up costs.

Two known methods to mitigate interference are antenna arrays and interference canceling multi-user detection. In the work performed by ASILUM the two methods are combined to provide a very powerful receiver combination. The work in ASILUM was split into two logical parts. The first part was to produce single cell results to show the frame error rate and bit error rate performance of the receivers with different user loading. To perform realistic simulations, a multiple antenna channel sounder has been built and a geometrical wideband directional channel model (WDCM) has been assessed from two realistic measurement campaigns, for macro-cell and micro-cell environments [13,14,15]. This model has been integrated in a Link Level Evaluation Platform (LLEP), which was used to assess the performances of various advanced receivers architectures mixing multiple antennas and multi-user detection.

The results from the link level evaluation are then used as input data to a system level evaluation platform. The system level evaluation determines the overall improvement in cell capacity and cell size in the system. Results indicate that large cell capacity increases are possible with the use of both interference canceling receivers and antenna arrays.

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The significance of the work done in ASILUM is of very important to the industry sector as the results show that

- Interference cancellation techniques are possible without changing the 3GPP specification for both UTRA-TDD and FDD,
- Large cell size increase and capacity increase is possible by using such techniques,
- Low complexity solutions for the receiver exist that could be realizable on real-time hardware, and
- Solutions to open problems, such as channel estimation, acquisition and tracking have been found, even when the receiver is operating in an extremely high interference environment.

2 Multi-User Receiver Techniques

Multi-user detection (MUD) has been a known method of reducing interference in a multiple users DS/CDMA system since the work of Verdu [22]. In this work it was determined that the optimal receiver, which cancels all interferences, has a complexity exponential with the number of users. Due to this high complexity and the conflicting requirements to design a high performance receiver, a lot of research over the last 15 years has been performed [23]. The aim of the investigations has to be to derive a low-complexity high-performance MUD solution. Each algorithm technique has it's own characteristics and advantages. In the ASILUM project, the most likely techniques have been selected and investigated. Below a quick summary of the techniques is covered before showing the results for each of the approaches.

A major goal of the ASILUM project is to propose efficient interference mitigation techniques that can operate with the 3GPP standard [1], are practical and provide good performance. The techniques were investigated for both the Time Division Duplex (TDD) and the Frequency Division Duplex (FDD) operating mode. From the above techniques the Parallel Interference Canceller (PIC) [10], and a Space-Time Joint Detector [12] were investigated for the TDD; Coded Interference Cancellation (Iterative MUD) was investigated for the uplink of the FDD [19]. Due to limited space the details of the techniques are not described in detail here but the reader is referred to the references [8, 9]. Below the multi-sensor PIC, the joint detection and the Iterative MUD results are shown as examples of the performance with the 3GPP standard.

2.1 Multisensor PIC for UMTS-TDD

The PIC structures studied in the present project approach have been considered in several papers [17,10], but most of the studies focused their performance in single antenna environments. Therefore, the objective is to extend this study to a multi-element environment for typical UMTS-TDD uplink scenarios. The specific PIC structures considered are [18,21]:

- **One stage PIC**: this structure estimates and subtracts in a single step all the MAI for each of the K users. This is the simplest PIC version.
- **Multistage PIC (two or more stages):** with this structure in each stage a decision attempt is made for each user to completely cancel the interference caused by all the other users. With this sort of PIC decisions performed in subsequent stages can be considered more reliable. However, for Soft Decision that may be not true.
- **Partial PIC**: it has been shown that when complete cancellation ("brute force") is attempted, a bias arises in the decision statistics. Partial interference cancellation mitigates the negative effects of biased estimation and significant improvement is achieved (especially in soft decision PIC).

A multisensor PIC was implemented to evaluate the performance achieved with these three approaches in an UMTS-TDD uplink. Figure 1 illustrates the BER improvement brought by a PIC architecture.

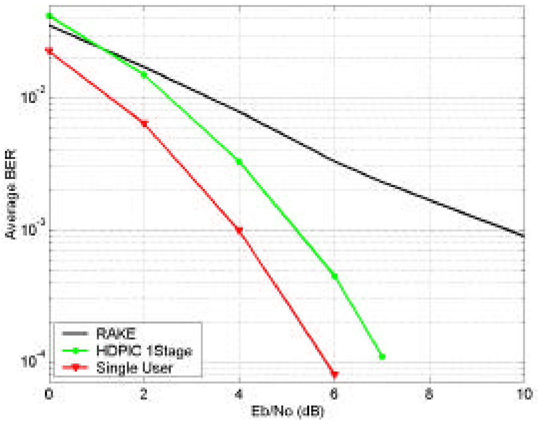

Figure 1: Performance comparison, after channel decoding, between the hard decision PIC scheme and a 2D-Rake, as function of Eb/No – WDCM (12 users) – Perfect channel estimation assumed.

The spreading factor is 16, Eb/No=10dB, antenna spacing is 0.45 wavelength.

The main conclusions with the PIC scheme are the following:

- The performance remains superior to that of a conventional RAKE.

- It has been shown that the performances of the all PIC schemes remain superior to that of the RAKE receiver.
- Significant improvement is achieved for all PIC schemes implemented when used in conjunction with 4-element circular array, as compared with single antenna. Hard decision PIC outperforms soft decision PIC in all scenarios due to a bias effect in the soft decision system. Use of more than one stage is only effective for high values of the load, more than 12 in scenarios with spreading factor equal 16.
- Complexity per user is independent of the number of users.

2.2 Multisensor joint detection for UMTS-TDD

A joint detector using multiple antennas has been developed for the uplink of the TDD mode. It has been studied in several papers [5,11], but a fractionally spaced implementation of the detector described in [5] has been considered in order to get robustness versus synchronization errors. The principle of the joint detection is to perform a joint demodulation of the received bursts, by using zero-forcing or MMSE equalizers. Compared with a conventional Rake receiver, the joint detector cancels both interference and the multiple access noise. The use of multiple antennas allows to perform a directional channel estimation, which improves the performance in the following ways:

- The benefit is all the more important since the directions of arrival of the signals of the different users are different.
- If the directions of arrival of the signals of the different emitters are enough distant from each other, the performances do not degrade with the number of emitters.
- A fractionally spaced implementation brings a robustness versus synchronization errors.

Figure 2 shows the performance result of the FS-JD using a directional correlation to estimate the directional channel impulse response, versus a 2D-Rake receiver, with the WDCM channel. The spreading factor of all emitters is 16. A uniform linear array with 4 antennas with a λ/2 spacing is used. Moreover, the directions of arrival of the signals are supposed perfectly estimated, the emitters are synchronous, and a fractionally spaced equalization is performed with 2 samples per chip.

FS-JD achieves considerable performance improvement when compared with a 2D-Rake receiver. Furthermore, in terms of implementation, the complexity increase relatively to the 2D-Rake receiver is moderate [9]. Results point out that the development of a FS-JD receiver is viable for UMTS-TDD uplink, with significant performance increase.

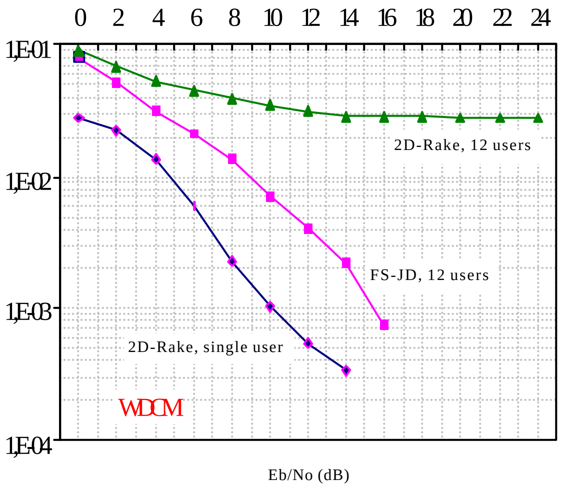

Figure 2: Performance of FS-JD vs. 2D-Rake on the WDCM, with 12 users, before channel decoding, and using a directional correlation to estimate the channel.

2.3 Iterative Multi-user Detection for UMTS-FDD.

This section is based on the concepts of Iterative Multiuser Detection (IMUD) [20]. An IMUD uses concepts from turbo codes [4] or more specifically serial concatenated turbo codes [3], where the CDMA system is viewed as the inner code and the outer code is the code associated with each user. When this system model is used, a receiver structure similar to a serial concatenated turbo decoder can be determined, which performs detection and decoding in an iterative or multi-stage way.

IMUD techniques have many variations and the complexity of the system depends largely on the implementation selected. In this work we utilize methods [2,6,16,19] as these methods have low computational complexity, where the total complexity increases at a linear rate with the number of users in the system. This type of receiver also allows for easy integration of antenna arrays. This is achieved while still being able to achieve the performance of the optimal receiver.

The result in Figure 3 shows the performance, over iterations (or stages), for a system with 4 antenna elements arranged as a uniform linear array with a 120 degree sector. Both the DOA and channel are estimated and the processing gain of 8, and 16 users are active. Perfect average power levels are again assumed. The channel is the Wideband Directional Channel Model (WDCM). This channel with this number of users is very challenging as seen by the extremely poor conventional receiver (labeled as "2D Rake") performance which has flooring at 1 error in 10 bits. The multi-user receiver design however overcomes this interference and can achieve a steep BER curve which is only 7.5dB away from a single user result (labeled as "1 user – Real estim."). Under this extremely difficult channel the loading factor (users/processing gain) of 1 is achieved. This is a remarkable result considering the complexity of the receiver, per user, is independent of the number of users. With this result we have a user to spreading factor ratio of approximately 2, which is substantially larger than current single antenna DS/CDMA systems available on the market.

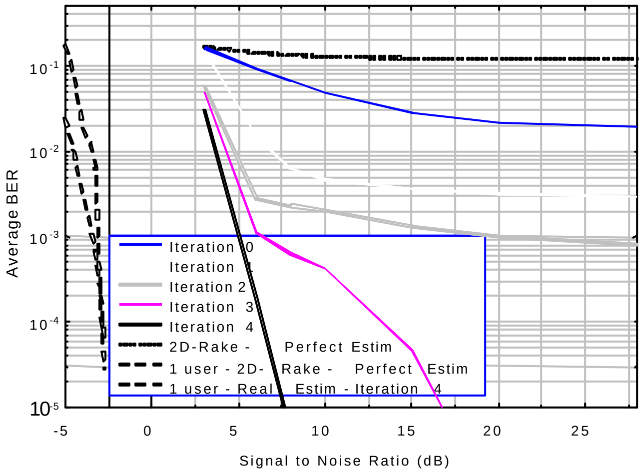

Figure 3: Influence of the number of iterations in the 144kbps FDD UMTS scenario – Adaptive Detection – WDCM – 16 Users

3 Integrating Link and System level simulations

ASILUM simulation methodology consisted in splitting the simulation effort into two simulators.

- At microscopic level and with a time resolution in the order of the chip duration, the actual transmitter/receiver digital communication chain is simulated in a Link Level Evaluation Platform (LLEP). LLEP focuses in simulating the actual physical layer of the UMTS system in a specific cell under fixed traffic conditions and fast fading channel.
- At macroscopic level, and with a time resolution of few tens of frames, the actual evolution of a mobile radio network is simulated in a System Level Evaluation Platform (SLEP) [7]. SLEP focuses in simulating all the layers of the UMTS system over a combination of multiple cells, and with varying near-far and traffic conditions.

LLEP and SLEP simulations are complementary. It was felt too complex to simulate an effective radio system with many cells at chip level, as well as inappropriate to simulate upper layers in signal processing tools. On the other hand, it was also felt important to check the impact of algorithms studied in LLEP also at the system level, with soft handover, actual near-far conditions, and realistic inter-cell interference distribution.

Among many other results previously mentioned in this paper, LLEP simulations also aimed at providing figures of merit of the receiver, to be later on used in the SLEP. SLEP uses a model of the physical layer which contains some parameters measured at LLEP level, so as to fit SLEP model with LLEP simulated reality. The figures of merit are basically

- the SINR (Signal-to-Interference-plus-Noise) required at the input of the turbo decoder to fulfill a target BER of BLER level,
- the multi-user detection factor α, being defined as the ratio between intra-cell MAI power level observed after the studied receiver and a reference receiver. The reference receiver is chosen arbitrarily as being the optimum Wiener beamforming followed by a conventional RAKE receiver with infinite number of fingers.

It is to be noted that LLEP simulations showed few variation of the SINR and the α values in multiple MAI configurations for a given receiver structure.

At SLEP level, the distribution of calls passing over the network is changed dynamically according to traffic generation models. The related mobile stations also change their position according to mobility models. Then, according to consequent near-far propagation variations, the SLEP Radio Resource Management (RRM) module decides the contents of the active set of each mobile station.

Finally, for each near-far call distribution, and the related MS-Cell connectivity, SLEP aims at solving for the power control equation that reflects the physical layer behavior. The unknowns are the transmit power levels P_i of all radio links. For each radio link, the slow power control loop is assumed to converge, and unless in power saturation cases, the SINR at the output of the single antenna receiver verifies :

$$SINR_i = SF \frac{P_i G_{i,f(i)}}{N_o + MAI_{ext} + \alpha MAI_{\text{int}} + SelfNoise}$$

SF being the used spreading factor, $G_{i,k}$ the coupling loss between the i^{th} mobile station and the k^{th} cell antenna connector. Similarly in beamforming solution, the above equation expresses as

$$SINR_i = SF \frac{P_i G_{i,f(i)} BF_{i,i}}{\left\{ N_o + \sum_{\forall j / f(j) \neq f(i)} P_j G_{j,f(i)} BF_{j,i} + \alpha \sum_{\forall j \neq i / f(j) = f(i)} P_j G_{j,f(i)} BF_{j,i} + \beta P_i G_{i,f(i)} BF_{i,i} \right\}}$$

where β is the channel orthogonality factor, $BF_{j,i}$ the gain observed for the j^{th} signal when applying the Wiener beamformer solution $g_i(\theta)$ optimized for the i^{th} signal :

$$BF_{j,i} = \int_0^{2\pi} w_j(\theta) g_i(\theta) d\theta$$

$w^j(\theta)$ being the spatial channel transfer function observed for the j^{th} signal. This transfer functions is also used in the link level simulations. To determine these functions, a wideband directional channel has been developed and assessed with channel measurement campaigns [13,14,15].

The gain $BF_{i,j}$ strongly depends on the relative spatial distribution of users, so that it was not possible to model this gain at SLEP level. Instead, SLEP computes the actual optimum Wiener solution $g_i(\theta)$, obtained as a well known function of the spatial distribution of the interfering powers P_i and the spatial distribution of the desired power.

Because $g_i(\theta)$ and P_i levels are linked together and cannot be determined separately, SLEP solves for the determination of those levels at once, while respecting the dynamic range of each radio link. To find the effective radio capacity of the system, SLEP increases the offered traffic in the system until the power saturation rate increases to a value for which the global user satisfaction rate gets below a 95% threshold.

4 System level simulations

The results of system simulations are detailed in [7]. We summarize in the following lines some conclusions from extensive simulation campaigns.

In FDD, optimum beamforming only is not sufficient to remove the maximum level of co-channel interference. Combination of beamforming and MUD-like receiver can strongly increase (more than double) the system capacity compared to beamforming-only solution. This is a remarkable result when one observes that the number of RF front-ends is kept same.

In TDD, the uplink capacity with multiple antennas per cell is very near the code-blocking limit, without the introduction of joint usage of joint detection and adaptive antenna array. Such techniques can be applied to increase the uplink capacity by an amount that depends on the algorithm complexity.

The code usage in TDD was designed to optimize the radio capacity of the system in unloaded situations, as well as to ease the implementation of complex TDD receivers. The number of codes available in the standard is low by construction, and can rapidly be reached with the introduction of smart detection techniques such as joint detection and adaptive antenna array, which aim at strongly increasing the radio capacity. As a conclusion, TDD has good capacity in single antenna situations, but is intrinsically code-limited and thus smarter techniques fail to radically increase the radio capacity in TDD.

On the other hand, the 3GPP standard provides a much bigger number of codes available in the FDD mode. While in a first approach, the capacity of FDD may be degraded compared with TDD in simple situations (because of lack of orthogonality between codes and thus higher MAI levels), the result is opposite when smart detection techniques are made available. FDD is intrinsically interference-limited, but has virtually no code limitation. In this sketch, any interference removal algorithm can efficiently raise its capacity, and joint usage of multi-user detection and adaptive antenna array proved to bring substantial capacity gain.

5 Conclusions

Single cell results show large performance improvements are possible when combining both interference cancellation techniques and antenna arrays. Antenna arrays inherently provide a noise reduction gain as well as interference reduction gains. Multi-user detection provides further improvement by reducing interference from other users further. The main conclusions from the single cell results are that interference cancellation techniques are possible without changing the 3GPP specification for both TDD and FDD; low complexity solutions for the receiver exist that could be realizable on real-time hardware; solutions to open problems, such as channel estimation, acquisition and tracking have been found, even when the receiver is operating in an extremely high interference environment.

A methodology to interface link level simulations with system level simulations has been described. It enables the provision of accurate system-level results of usage of combined beamforming and multi-user detection schemes.

System simulations performed have highlighted the fact that since a much bigger number of codes are available in the FDD mode than in the TDD mode, smart detection techniques bring more benefits in FDD than in TDD mode in terms of capacity improvements. This current limitation of the TDD mode in the 3GPP standard could be avoided by the introduction of additional codes.

6 References

[1] 3G TS 25.212 V3.5.0 "3rd Generation Partnership Project: Technical Specification Group Radio Access Network; Multiplexing and channel coding (FDD)".

[2] P. Alexander, A. Grant and M. Reed, "Performance Analysis of an Iterative Decoder for Code-Division Multiple-Access", European Trans. on Telecommunications, vol 9, pp 419-426, Sep./Oct. 1998.

[3] S. Benedetto and G. Montorsi, "Iterative Decoding of Serially Concatenated Convolutional Codes", Electronic Letters, vol. 32, June, pp 1186-1188, 1996.

[4] C. Berrou, A. Glavieux, and P. Thitmajshima, "Near Shannon Limit Error-Correcting Coding and Decoding: Turbo-Codes", May, IEEE Int. Conf. on Communications, Geneva, Switzerland, pp 1064-1070,1993.

[5] J.J. Blanz, A. Papathanassiou, M. Haardt, I. Furio, P.W. Baier, "Smart antennas for combined DOA and joint channel estimation in time-slotted CDMA", IEEE Trans. On Vehicular Technology, vol. 49, no.2, pp 293-306, 2000.

[6] L. Brunel and D. Mottier, “Iterative interference cancellation scheme with pilot aided space-time estimation in DS-CDMA systems”, in Proc. of VTC'01, Vehicular Technology Conference, Atlantic City, USA, 7-11 Oct. 2001.

[7] Deliverable D3.3 “Final report on system evaluation results”, available at www.ist-asilum.org.

[8] Deliverable D4.4 "Final Report on the Evaluation of the Different Algorithms in terms of Link Performance", available at www.ist-asilum.org.

[9] Deliverable D4.6 “Synthesis report on the performances versus implementation complexity”, available at www.ist-asilum.org.

[10] D. Divsalar, M.K. Simon and D. Raphaeli, “ Improved Parallel Interference Cancellation for CDMA”, IEEE Transactions on Communications, Vol. 46, No.2, February 1998.

[11] P. Jung, J.J. Blanz, "Joint detection with coherent receiver antenna diversity in CDMA mobile radio systems", IEEE Trans. On Vehicular Technology, vol. 44, no.1, pp 76-88, 1995

[12] P. Jung, J. Blanz, P. Baier, "Coherent receiver antenna diversity for CDMA mobile radio systems using joint detection", Proc. IEEE Int. Symp. on Personal, Indoor and Mobile Radio Comm. (PIMRC 1993),Yokohama, pp488-492

[13] G.Marques and L.M.Correia, "A Wideband Directional Channel Model for UMTS Micro-cells", Proceedings of PIMRC2001 – 12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, San Diego, California, USA, Sep. 2001.

[14] G.Marques, E.Zollinger, J.Kunisch, S.Weitz, J.Siemons, J.Pamp, and L.M.Correia, "Modelling and Measuring Wideband Directional Channels for UMTS Micro-cells", IST Mobile Communications Summit, Barcelona, Spain, Sep. 9-12, 2001

[15] "Micro-cell Wideband Directional Channel Model", 3GPP TSG RAN WG 1, document TSG R1#22 R1-01-0992, New York City, NY, USA, October 23 – 26, 2001, www.3gpp.org.

[16] D. Mottier and L. Brunel, “A low complexity turbo-adaptive interference cancellation using antenna arrays for W-CDMA.”, in Proc. of VTC'01, Vehicular Technology Conference, Atlantic City, USA, 7-11 Oct. 2001.

[17] S. Neiyer, R. Correal, M. Buehrer and B. D. Woener, “A DSP-Based DS-CDMA Multiuser Receiver Employing Partial Parallel Interference Cancellation” IEEE Journal on Selected Areas in Communications, Vol. 17, No. 4, April 1999.

[18] P. Pinho, A. Morgado, L. Gonçalves, J. Fernandes and A. Gameiro, “Link Level Evaluation Platform with Space-time Processing for UMTS-TDD”, in Proc. of Conftele 2001 – 3rd Conference on Telecommunications, Figueira da Foz, Portugal, Apr. 2001.

[19] M. C. Reed and P. D. Alexander, "Iterative Detection using Antenna Arrays and FEC on Multipath Channels", IEEE Journal on Sel. Areas in Comm., vol. 17, pp.2082-2089, Dec. 1999.

[20] M. C. Reed, C. B. Schlegel, P. D. Alexander, and J. A. Asenstorfer, "Iterative Multiuser Detection for {CDMA} with {FEC}: Near Single User Performance", IEEE Trans. on Comm. vol. 46, pp 1693-1699, Dec. 1998.

[21] A. Silva, A. Gameiro, “Performance evaluation of multisensor parallel interference cancellation for the UMTS-TDD uplink”, in Proc. of Wireless Personal Multimedia Communications, September 2001, Denmark.

[22] S. Verdú, "Minimum Probability of Error for Asynchronous Gaussian Multiple-Access Channels", IEEE Trans. in Inf. Theory, vol. 32, pp.85-96, Jan. 1986.

[23] S. Verdú, "Multiuser Detection", Cambridge University Press, 1998