SIXTH FRAMEWORK PROGRAMME
PRIORITY 2
Information Society Technologies IST

ACE
Antenna Centre of Excellence

Deliverable 2.2.D9
System Level Performance Optimisation of Smart Antenna Networks

Contractual Date of Delivery to the CEC:	*31 December 2005*
Actual Date of Delivery to the CEC:	*9 January 2006*
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Workpackage:	*WP2.2-4*
Security:	*PU*

Executive Summary

In this deliverable, the joint research activities within the framework of ACE in the area of System Level Strategies and Cross Layer Optimisation for Smart Antenna Networks are presented. The main objectives of joint research activities were to maximise integration among the ACE partners and spread the excellence through education and dissemination within the ACE community and to the European and international research community.

At the beginning of the ACE project the partners with expertise on these research themes were faced with the challenge to coordinate the knowledge and skills and come up with a common workplan for interaction, collaboration and dissemination of the knowledge at the European and global level. To this end the state-of-the-art was reviewed and knowledge gaps were identified. Based on the identified knowledge gaps, integration was achieved by organising joint research around two main tasks: 1) Study of multi-user transmission challenges and limiting factors and optimisation of scheduling schemes and radio resource management in varying radio propagation, traffic and service conditions, and 2) System level performance cross layer optimization criteria based both on Quality of Service (QoS) and throughput.

Along the lines of the above research themes the ACE partners have worked on spreading the excellence by organising short courses and supervising Masters and PhD projects in this area. Moreover, the research activities have been disseminated extensively on national and European level. Finally, two major dissemination/spreading the excellence events, one workshop and one special session at a conference, were successfully organised by ACE and attracted the interest of the European and international research community.

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1 Introduction

It has become apparent in recent years that performance evaluation of Smart Antenna systems at the link level cannot provide a realistic validation of the achieved enhancements, as the gains at the link level do not necessarily translate to equivalent system level gains, due to the effect of interference resulting from the resource management techniques and the multiple access scheme deployed.

In this deliverable, **system level re-configurability strategies for smart antenna networks** are investigated. Starting from reviewing the state of the art, initially the achievements and objectives of relevant EU funded projects (completed and/or ongoing) are examined. Examples include the IST Projects ASILUM, METRA, I-METRA, SHUFFLE and MONASIDRE.

In addition, emphasis is given in the area of **link to system level interface**. Simulation complexity constraints impose a trade-off between the amount of higher layer system functionalities (e.g., ARQ, scheduling, hand-over) to be reflected in system level analysis and the accuracy of the representation, especially in the Smart Antenna case, where space diversity introduces an additional dimension. In order to optimise this trade-off, an interface between link and system level studies can be devised, relying on a carefully selected interface parameter that uniquely characterizes both link and system performance. The closer to one-to-one this mapping is, the more accurate the interface.

In a multi-user context, the problem of **scheduling** has recently received considerable attention, as optimisation of scheduling strategies can offer significant system throughput gains. Within the framework of ACE, multi-user scheduling is studied for multi-carrier systems that are widely deployed due to their ability to combat multi-path by converting the time-selective channel into a set of parallel and independent flat fading subchannels. Moreover, in order to improve the performance of multi-user MIMO systems, opportunistic approaches can be applied. The basic idea is to multiplex users by granting the channel to those with higher chances of completing a successful transmission. For specular spatial channels, opportunistic beamforming approaches point at the user with the highest SNIR out of those present in the system. In rich-scattering scenarios opportunistic approaches exploit fading by granting access to those with highest instantaneous capacity.

The overall system performance can be further enhanced by interacting with the higher layers of the OSI/ISO (Open Systems Interconnection model of the International Standards Organization) protocol stack. Smart Antenna techniques can be developed combining parameters in the physical, link (Medium Access Control - MAC, Data Link Control - DLC, scheduling, etc) and network layers (radio resource management, routing, transport, etc), that is, in a **cross-layer** fashion rather than attempting to optimize the designs in isolation of one another.

At the beginning of the project, several institutions in Europe performing first-rate research on these topics, were faced with the challenge to coordinate the expertise and skills in the area and come up with a common plan for interaction among researchers, directions of future research and dissemination of the knowledge and expertise at the European and global level.

The objective during the first part of the project has been to review the state-of-the-art on Smart Antenna system level strategies, and to identify the knowledge gaps. The identification of gaps has provided the grounds for drawing a specific action plan for interaction, collaboration and dissemination activities.

1.1 Progress towards objectives

Research Activities:

The research activities described in the deliverable have been structured around two tasks:

- **System Level Strategies for Smart Antenna Networks**: Study of multi-user transmission challenges and limiting factors and optimisation of scheduling schemes and radio resource management in varying radio propagation, traffic and service conditions. Review of state of the art and identification of knowledge gaps.

- **Cross Layer Optimisation Strategies**: System level performance optimization criteria based both on Quality of Service (QoS) and throughput are investigated.

Integration Activities:

The integration activities carried out, in the framework of the research themes described in the previous paragraph, can be summarized as follows.

- **Identification of scientific and technical know-how.** An extensive review of the technical and scientific know-how of each partner has been carried out, in order to identify the potential ground for collaboration and the open knowledge gaps. The scientific and technical know-how was specified based on past collaborations in research projects, simulation platforms development and publications.
- **Identification of knowledge gaps**. Based on the review of state of the art on system level strategies and cross layer designs for Smart Antenna systems and the identified know-how and research interests of the partners, the work has been structured around two tasks as described above. For each task, identification of the most important/interesting knowledge gaps has been made and an action plan for future research collaboration and integration activities has been formulated.
- **Elaboration of an action plan for collaboration.**
    - ICCS, LUCENT, IT and KTH are collaborating on system level performance evaluations, in particular on the Link to System Interface problem and remaining open issues.
    - CTTC, ICCS, IT, KTH, UPRC, UPM and LUCENT are collaborating on common research plan and dissemination in the area of packet scheduling algorithms for wireless channels, combining QoS related and PHY layer information. A special session on these research topics has been organized at the IEEE PIMRC 2005 conference.

These integration activities have been planned and monitored through several work package meetings and phone conferences. All partners were represented at the meetings and have actively participated by giving technical presentations and being involved in the discussions. (The meeting minutes and partners presentation can be found on the VCE.)

Dissemination, Spreading the Excellence and Education Activities:

Within ACE spreading the excellence/dissemination activities include:

- PhD/Masters students project at IT, ICCS, KTH focusing their research on Smart Antennas System Level Strategies and Cross Layer Optimisation.
- Short courses and lectures.

The work developed under the umbrella of this work package has been submitted to and published in several journals, such as:

- IEE Electronics Letters
- IEE Proceedings in Communications

- IEEE Communications Magazine
- IEEE Wireless Communications Magazine

and international conferences, such as:

- IEEE Vehicular Technology Conference
- IEEE Sensor Array and Multichannel Signal Processing Workshop
- IEEE GLOBECOM
- IEEE PIMRC
- WWRF meetings.

Moreover, ACE activities have been disseminated extensively on national, European and international level, including IST events, such as the IST concertation and clustering activities, the IST Mobile Summit.

Finally, two major dissemination/spreading the excellence activities were carried out:

- A special session on Cross-layer PHY-MAC/scheduling designs was organised at the IEEE PIMRC 2005 conference in Berlin (September 11 - 14, 2005). Moreover, two of the members of the Scientific Council participated in this conference as keynote speakers sponsored by ACE.
- An ACE workshop on Smart Antennas was organized at the IST Mobile Summit 2005, in Dresden (23 June 2005).

2 Joint Research Activities

2.1 System Level Strategies for Smart Antenna Networks

The importance of system level evaluation of space-time processing techniques is critical, as the performance gains obtained by the application of these techniques at the link level may not translate to equivalent gains at the system level. On the other hand, the evaluation of the benefits of multiple antenna techniques at the system level introduces a number of challenges, such as the requirement for suitable spatio-temporal channel modelling, for accurate modelling of the inter-cell interference, the network deployment characteristics, the traffic and load conditions and the optimisation of the trade-off between simulation complexity and accuracy, by means of the identification of a suitable link to system level interface.

The system level simulator input should be specified according to a predefined number of test cases, each consisting of specific space-time algorithms, antenna configurations, propagation environment, mobility and user requirements. A suitable interface between link- and system-level simulations should be described by a metric, which can appropriately encapsulate the performance of the receiver, say in terms of the probability of frame error, given the prevailing radio environment (specific channel realization) over the packet duration. The goal is to be able to evaluate the probability of frame error at any instant for a particular user, provided the user's channel matrix (M transmit and N receive antennas are assumed in the general case), interfering channel matrices symbol energy and thermal noise energy.

The complexity involved in a system level evaluation is naturally associated with the dimensionality of the system parameters, such as the number of antennas, carriers, users, propagation conditions, traffic patterns on the one hand and, on the other, with the time scale and the system level functionalities that need to be reflected. Detailed representation of fast adaptation and scheduling would require a large number of parameters to be considered and averaging in this case may result in loss of accuracy.

In the following sections the state of the art in system level methodology is first presented, followed by a discussion on the identified knowledge gaps. Finally, the latest developments and the outcome of the ACE partners research activities and future actions are presented.

2.1.1 State of the art and critical parameters in system level performance evaluation for Smart Antenna Networks

In this section the state of the art in system level methodology for Smart Antenna networks is presented based on work performed by ACE partners in collaboration with other organisations in Europe in the framework of a number of past research projects:

- ASILUM [1]
- METRA [3]
- SHUFFLE [4]
- MONASIDRE [6]
- FITNESS [8]

In the following paragraphs the main objectives of each project will be presented along with their proposed approached with respect to the system level methodology.

2.1.1.1 The ASILUM Approach

ASILUM stands for **A**dvanced **Si**gnal Processing Schemes for **L**ink Capacity Increase in **UM**TS.

The objective of the ASILUM project was to validate new transceiver concepts, for both base station and mobile terminals, in order to increase the capacity of the future generation of UMTS through new and efficient interference mitigation schemes. These techniques have been optimally combined to provide innovative improved interference mitigation schemes together with high hardware efficiency. A software-based simulation platform developed to evaluate a number of competitive techniques was designed, implemented and validated. The studies performed included the thorough analysis of the latest developments in the standards and at the end of the project, a set of recommendations have been submitted to the relevant standardisation bodies.

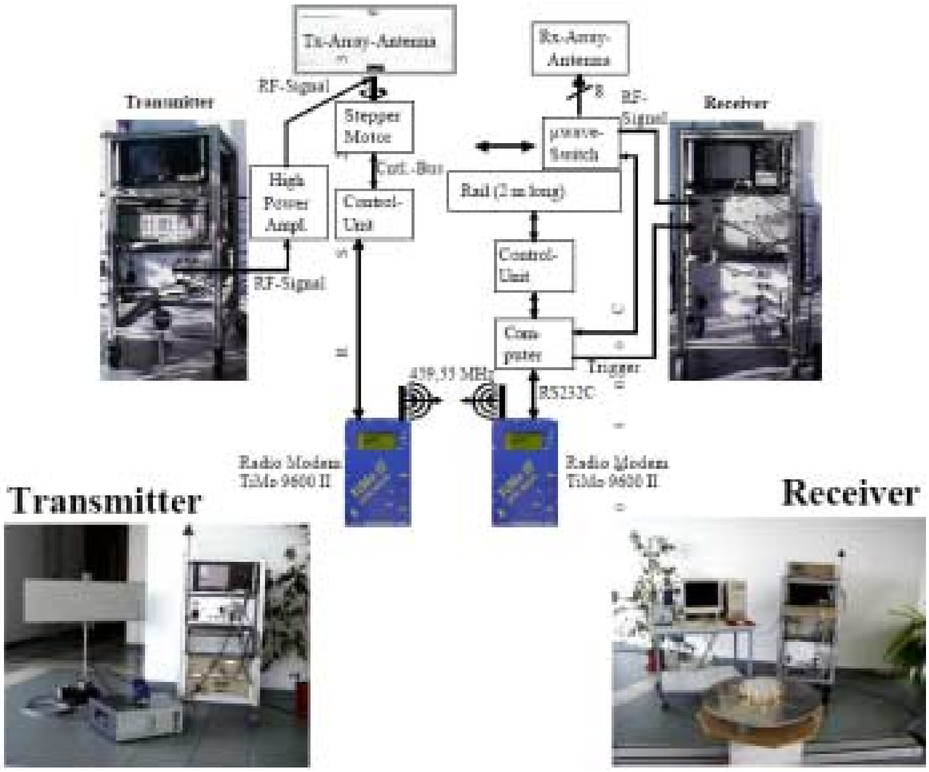

Figure 1: Experimental set-up extracted from ASILUM (source ASILUM, [1])

The ASILUM project focused its investigations on the following techniques:

- Space-time processing schemes at the base station and the mobile terminal such as a combination of smart antennas and blind/non-blind multi-user detection techniques;
- Beamforming techniques for space division multiple access (SDMA);
- Coding/decoding schemes including turbo codes and space-time codes in the downlink, and
- Hybrid digital/analog signal processing schemes where digital baseband processing benefits from an analog pre-processing at the radio frequency (RF) / intermediate frequency (IF) stages.

The ASILUM simulator consists of two evaluation platforms:

- The Link Level Evaluation Platform (LLEP) simulates the physical layer of UMTS in a specific cell, under fixed traffic conditions, with fast fading and chip resolution.
- The System Level Evaluation Platform (SLEP) simulates all layers of UMTS over a combination of multiple cells and time varying near-far and traffic conditions, with time resolution of few tens of frames.

Interface between Link and System Level Simulation Results

In order to interface the results to the SLEP, the ASILUM project uses a physical layer model, which contains parameters evaluated at LLEP:

- The SINR required at the input of the FEC decoder to achieve the target BER or BLER according to a QoS criterion,
- The Multi-User Detection (MUD) factor α defined as the ratio of intra-cell Multiple Access Interference (MAI) energy after the receiver under investigation over the intra-cell MAI energy after a reference 2D-Rake receiver, consisted of an optimal Wiener beamformer followed by a conventional Rake with infinite number of fingers,
- The beamformer simulated in both LLEP and SLEP to account for the varying conditions in terms of traffic and users spatial distribution.

The most important part of the link-system interface is to ensure that the scenarios interfaced between LLEP and SLEP represent the same physical reality. To this end, the coefficient α represents the additional interference reduction achieved by the receiver algorithm simulated in LLEP as compared to the reference receiver simulated in SLEP, that is a Wiener beamformer for each user followed by a conventional Rake receiver with Maximum Ratio Coupling (MRC). Although the coefficient α should be computed after decoding, this would require soft output decoding. To allow the use of hard decoding and further simplify the analysis, the coefficient α was computed before decoding, assuming that the MAI remaining after multi-user detection is like AWGN and cannot be further suppressed by decoding, and therefore assumes that coefficient α is the same if computed before and after decoding.

The evaluation of SINR and the coefficient α is based on the results of three simulation chains. The evaluation of SINR is based on energy measurements in the multi-user and the single user reference chain. The evaluation of the coefficient α requires also the simulation of the 2D-Rake reference chain and can be based either on energy measurements in the above three chains for constant noise level or on the difference in the required SNR for a certain target BER between the multi-user and the single user case.

System Level Simulation Methodology

The main features of the ASILUM system level simulator are:

- Dynamic input simulation scenario: a succession of scenarios is generated in a dynamic way, by modifying the system in terms of traffic distribution and near-far distribution of users;
- Dynamic radio resource management: a realistic UMTS network is simulated with nearly optimized RRM, so that the resulting gains from the use of advanced techniques, such as multi-user detection and beamforming can be evaluated;
- Power control convergence simulation: the challenges of the power control convergence problem due to the constraints in the available power, the soft handover and the spatial distribution of the received power in a multiple antenna system are addressed in SLEP by using the coefficient α, and

- Capacity results: for a given scenario, the limit capacity (in kbps/MHz/Cell), which the system can maintain, is computed based on the subscriber density, according to the 95% criterion of user satisfaction at the required QoS grade.

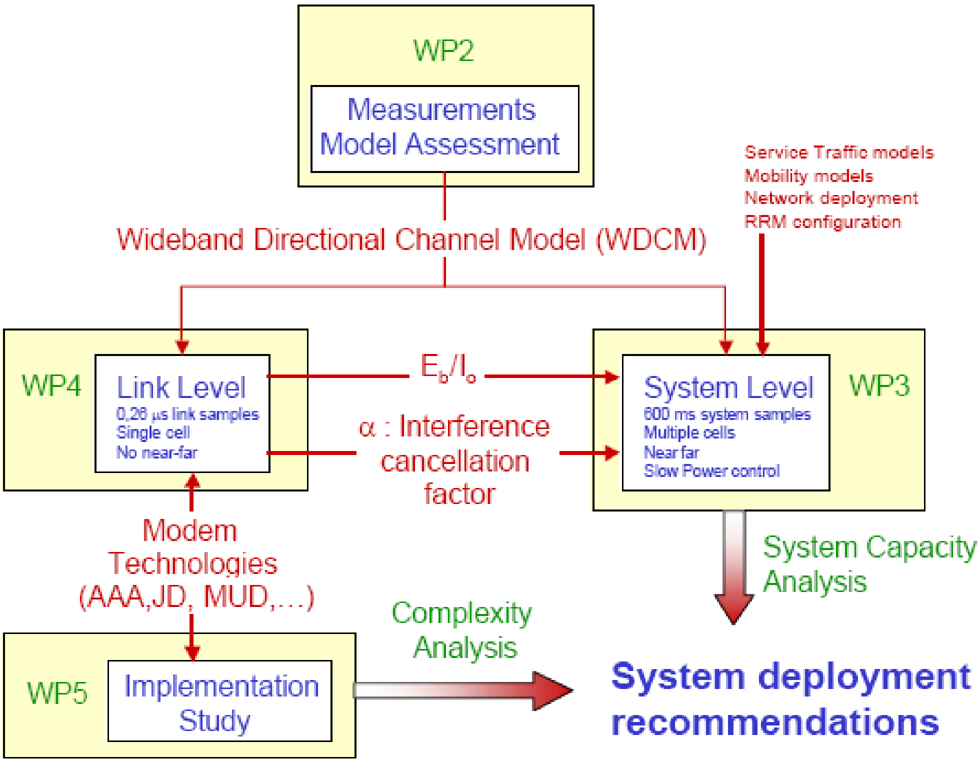

Figure 2: ASILUM simulation Flow Diagram (source ASILUM, [1])

2.1.1.2 The METRA Approach

METRA stands for **M**ulti-**E**lement **T**ransmit and **R**eceive **A**ntennas

The main objective of METRA was to analyse the feasibility and evaluate the performance of introducing multi-element adaptive antennas into mobile terminals in combination with adaptive base station antenna arrays for UMTS.

On the other hand, the key issues of METRA project was to perform multiple-input and multiple-output (MIMO) matrix radio channel measurement in order to clarify the characteristics of the MIMO channel matrix in various mobile communication scenarios. The performance of various transmit and receive options have been analysed under realistic conditions, i.e. propagation, MAI, and other UMTS system aspects.

Also, the METRA project performed a pseudo real-time demonstration of transmit and receive diversity concepts for UMTS via a Monte-Carlo type simulator, where static snapshots of possible network realizations are generated based on a particular user distribution, services scenario and user density. The model did not include mobility or fast fading.

System Level Simulation Scenarios

For the system level simulations the following input parameters are considered:

- Realistic distribution of base stations based on existing site locations,
- Coverage figures base on high resolution propagation data maps,
- Traffic distributions derived from GSM traffic data,
- Network parameters such as admission control and handover,
- Service types.

Different services are modelled by describing different link requirements for each service type. Different path-loss values are used to reflect changing propagation conditions (outdoor, indoor) and activity factors to model packet services.

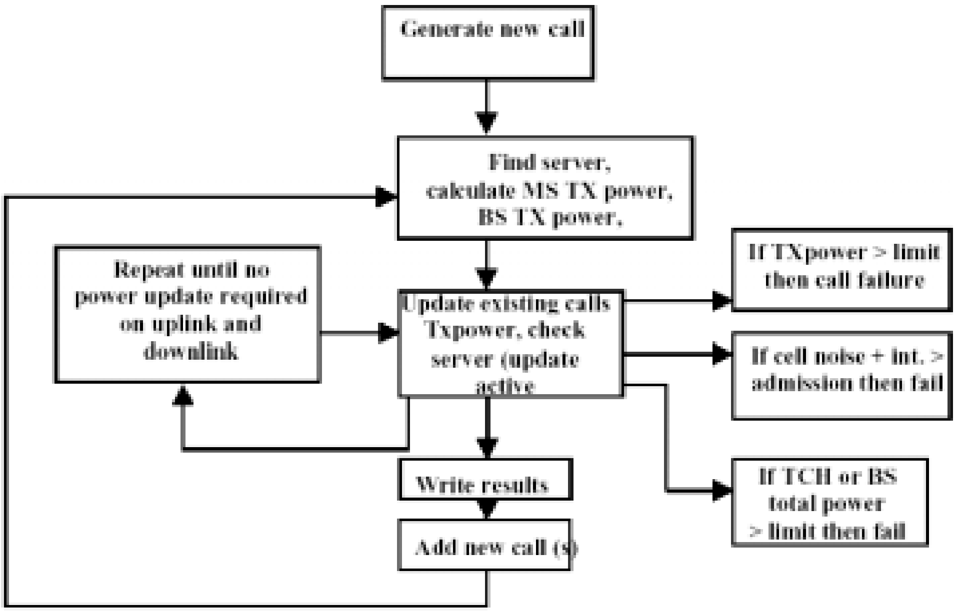

Figure 3: UMTS Simulator Flowchart (source METRA, [3])

When a new call is generated:

- Its location is determined according to the traffic distribution;
- The best server is established and the minimum User Equipment (UE) transmit power and node B transmit power to maintain the connection are calculated;
- Due to the increased interference in the network all other calls' powers are updated (uplink power control) and all cells powers are also updated (downlink power control);
- The calls are checked to determine if any failure conditions have been met;
- Steps 3 and 4 are repeated until the power control is stabilized and the results are then recorded;

- More calls are added into the network.

The snapshot ends when the number of calls failures causes the network Grade of Service (GoS) to fall below its desired value. The simulator generates a number of outputs, both overall and for the individual services:

- Capacity: total and per cell,
- Power requirements: base station and terminal,
- In-cell to out-cell interference ratios,
- Graphical output of active and failed calls.

The simulator can operate in three modes:

1. Uplink and downlink,
2. Uplink only, and
3. Downlink only.

Interface between Link and System Level Simulation Results

The system simulator uses link-level results in order to assess the system level gains of MIMO techniques. The link-system interface is based on the propagation environment considered and parameters G and F, representing the intra- to inter-cell interference ratio for the downlink and uplink respectively. For a particular environment and value of the parameters G/F, performance gains in the required transmitted SNR are taken at a Frame Error Rate (FER) performance that assumes that the link requirements are satisfied.

2.1.1.3 The SHUFFLE Approach

The project has created a novel architecture for efficient, scalable and robust real time control of resources in 3rd generation mobile systems in the context of realistic business models of network providers, service providers and customers.

The main objectives of SHUFFLE were:

i) To implement advanced and distributed software technologies (particularly Intelligent Agent Technology) in a resource configuration system that dynamically allocates radio and associated fixed network resources in third generation mobile communication systems in order to provide:

- End-users with an improved and more cost-effective service, and
- Operators with increased opportunities for contingency management where for financial, social, safety or environmental reasons, allocation policies need to be dynamically changed

ii) To evaluate how the resulting resource allocation system improves the overall performance of the network (in particular assessing its adaptability to localised high traffic demands and fluctuations) and to compare the scheme with more centralised approaches.

iii) To disseminate the results of this work and to promote Agent Technology in Standards bodies.

iv) To include in the distributed intelligence, mechanisms to take into account the business objectives of the network operator, multiple service providers and customers and to investigate how these objectives affect resource allocation decisions.

The SHUFFLE project uses an agent-based management scheme simulation platform, which includes the following s blocks:

- **UMTS Environment Representation (UER):** This component represents the service area layout, and especially the partitioning into cells, to evaluate the traffic volume and the mobility level per portion of the service area (cell) and to compute the cross-interference among subsets of the service area.
- **UMTS Network Representation (UNR):** It provides the means for representing UMTS network configurations and hence, it consists of models that correspond to the UMTS network elements.
- **UMTS Simulator Event Scheduler (USES):** It provides the means for representing, storing, and manipulating (i.e. inserting, retrieving, deleting, etc.) the events that the core of the simulator (UMTS configuration) will have to handle.
- **UMTS Simulator Controller (USC):** It co-ordinates the other components of the platform.
- **Graphical User Interface (GUI):** during the initialization phase, the role of the GUI to enable the user to instantiate the test case. During the core simulation phase, this component will enable the user to readily monitor the environment conditions and the associated system performance by gathering and visualizing information on the service area conditions and the network performance.
- **Interface with the Agent Platform (IAP):** The IAP module is responsible for interfacing with the agent platform.

Figure 4 illustrates the flowchart of the SHUFFLE Platform:

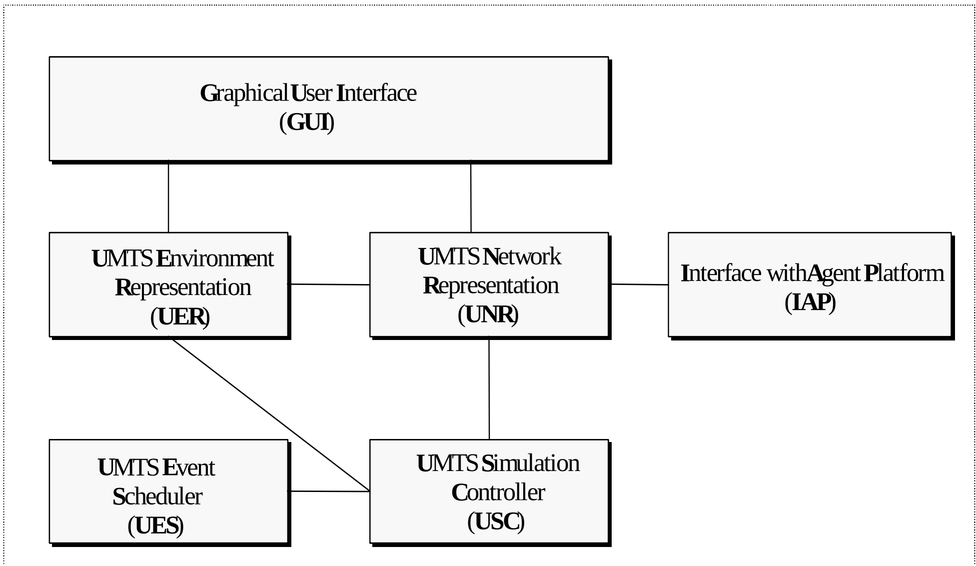

Figure 4: The SHUFFLE Platform (source SHUFFLE, [4])

2.1.1.4 The MONASIDRE Approach

MONASIDRE stands for **M**anagement **O**f **N**etworks **A**nd **S**ervices **I**n a **D**iversified **R**adio **E**nvironment.

The project assumes that UMTS, HIPERLAN and Digital Broadcasting Systems (DBS) will be three co-operating and complementary components. Through this infrastructure operators are able to provide users with efficient (in terms of cost and QoS) wireless access, and service providers with the means for offering sophisticated services.

The MONASIDRE main objectives were:

- Monitoring and analysing the statistical performance and the associated QoS levels provided by the network elements.
- Inter-working with service provider mechanisms, so as to allow service providers to dynamically request the reservation (release, etc.) of network resources.
- Performing dynamic network planning as a result of resource management strategies to optimise delivery of services to mobile users under a spectrum limited constraint
- Mapping adequately the IP based network resources to the radio resources

The main key issue in MONASIDRE related to smart antenna networks was the dynamic air interface configuration. Dynamic spectrum assignment aspects and dynamic configuration of radio access point air interface have been investigated.

The MONASIDRE system level simulator aims at implementing a network and service management platform for highly heterogeneous networks, especially for UMTS, HIPERLAN/2 and Digital Broadcasting Systems (DBS). The main goals of the system simulator are the following:

- Definition of interfaces with the (highly heterogeneous) elements or segments of the managed UMTS, HIPERLAN/2 and DBS infrastructure
- Integration of sophisticated managed system monitoring methodologies and procedures
- Definition of interfaces with the service provider mechanisms
- Contracts with service providers processing, establishment and maintenance
- Multiple air interface optimization, in the sense of allowing operators to operate or co-ordinate operations of heterogeneous wireless systems
- Dynamic air-interface configuration, i.e., determination of cost-effective radio resource configuration patterns that satisfy service providers' requests or new environment conditions, dynamic spectrum assignment aspects and corresponding configuration of radio access points, radio resource control strategies (e.g. call admission control, handover thresholds, etc.) activation (cessation, etc.)
- Dynamic configuration of the access network and/or the interface with the core network in an all-IP context.

2.1.1.5 The FITNESS Approach

FITNESS stands for **F**ourth Generation **I**ntelligent **T**ransparent **N**etworks **E**nhanced through **S**pace-time **S**ystems.

FITNESS has addressed the design of re-configurable Multiple Transmit and Multiple Receive (MTMR) transceivers and corresponding system level control mechanisms for their incorporation into composite radio environment, i.e. multi-technology radio networks. This technology allows re-configurability (adaptivity) to propagation channel characteristics, traffic conditions, service requirements and number of available antenna configurations at the access points (base station) and terminals. Hence, it achieves improved spectral efficiency at the link level as well as increased capacity at the system level and provides interoperability in a composite radio systems environment. The access technologies considered in the FITNESS studies are UMTS and WLAN.

The re-configurable MTMR techniques developed in the framework of FITNESS were evaluated at the link and the system level for both UMTS and WLAN. MTMR re-configurability at the system level addressed the investigation of intra- and inter-system operation mechanisms as well as the evaluation and validation of performance enhancements with re-configurable MTMR technology utilizing the FITNESS simulation platform.

The basic assumptions for the implementation of the FITNESS system-level simulator are as follows:

- Cell deployment assuming a network of cells
- Propagation modelling, utilizing suitable models for the path loss and shadow fading in an urban and suburban environment
- MIMO Channel modelling based on a geometry-based model. (For the sake of simplicity a correlation based model has been used instead when the investigated multiple antenna technique did not require the explicit incorporation of the angular parameter.)
- User mobility
- Two packet switched services are simulated in the downlink only: Web browsing and FTP.
- Traffic Pattern assuming that all users are in an active session. The adoption of this model results in generating a certain load with a smaller number of users, and hence reducing the complexity and simulation time.
- Packet scheduling performed by every sector base station.
- The system level performance is evaluated in terms of user and system throughput as well as the number and percentage of satisfied users.

The use of the information theoretic channel capacity C [10] has been proposed [11] as a suitable link to system level interface metric. The capacity metric under the assumption of Gaussian interference, where only the received power of the interfering users is accounted for and not their channel structure, was shown [9], [22] to be a suitable link to system level interface metric in the case of a large (>2) number of intercell interferers. Based on this observation and the relatively low computational complexity, this metric was selected for the link to system interface employed in the analysis carried out in FITNESS.

The initialization of the system level simulation involves the placement of base stations in the coverage area of the wireless network, the placement of the mobiles within each cell, the evaluation of path loss and shadowing from each base station to each mobile and the identification of a serving base station for each mobile based on the computed losses. In the main simulation loop, it is checked whether the position of every user should be updated. In this case, the signal strengths between all considered transmitters and receivers are calculated. The average signal-to-interference-plus noise ratio (*SINR*) is evaluated taking into account the transmit power, the path loss and shadow fading for the desirable signal and interfering links from all other cells in the network along with the thermal noise. Link adaptation mechanisms are activated. For every frame, MIMO channels for the wanted signals at all mobiles need to be simulated including fast fading. To determine the FER performance of a mobile receiver in conjunction with a specific MIMO channel realization, we make use of the information theoretic capacity metric C. The performance of the mobile receivers is assessed by consulting pre-computed curves, which associate FER to the capacity metric and are derived from link level simulations. At the end of the simulation time, statistical results from the simulated network are gathered and processed. The simulation procedure is depicted in Figure 5 in flow chart format.

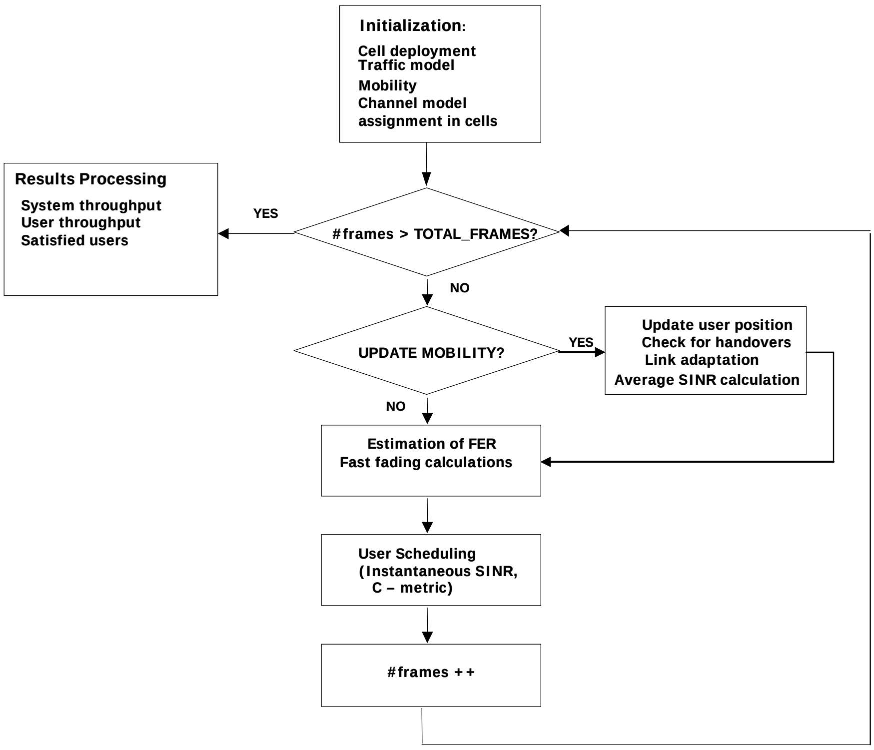

Figure 5: FITNESS system-level simulation procedure flow chart (source FITNESS, [8],[9])

2.1.2 Partners Know-How and Identification of knowledge gaps

In the framework of the above-described research projects and the system level analysis performed therein, the ACE partners have acquired expertise in the methodology, critical parameters, performance metrics of interest and implementation challenges associated with the performance evaluation at the system level. Most important, they have a good understanding of the trade-offs between complexity and accuracy, time scale and representation in details of the fast fading effects and of the impact of the MIMO channel on the intra- and inter-cell interference modelling for different multiple antenna techniques.

An assessment of the state of the art in the area summarised in the following paragraphs can help identify the knowledge gaps and interesting research directions:

- The approach in ASILUM manages to capture the impact of Multi-User Detection and Adaptive Antenna techniques in a dynamic system scenario where Radio Resource Management (RRM), Power Control (PC) and mobility are taken into account. The selection of deployment scenarios and the interface between link and system level results are based on the coefficient α, which reflects the interference reduction capability gain of the multiple antenna techniques under investigation as compared to the reference case of a Wiener beamformer followed by a Rake receiver. Although the use of coefficient α is tailored to characterize performance of the techniques considered in ASILUM, it cannot be generalized to be applicable to other multiple antenna techniques.
- The approach in METRA uses an interface metric between link and system level results based on the assumption that the (scalar) value of intra- to inter-cell interference ratio fully characterizes the

scenario. In that way the impact of the spatio-temporal structure of the desirable user and interference signals is not taken into account and therefore the capability of different techniques to cope with this kind of impairments is averaged out and cannot be reflected in the comparisons. Moreover, the METRA approach does not take into account the dynamics of the system in terms of fast fading and mobility.

- MONASIDRE simulator concentrates on management issues and incorporates functionalities of higher layers. However, it does not take into account link level simulation and it is implemented for the Single Input Single Output (SISO) case only.
- The FITNESS approach takes into account the MIMO channel of the desirable user by employing the channel capacity as an interface metric. The simulation also accounts for the dynamics of the systems, in terms of fast fading and mobility. However, only the received power of the interfering users is accounted for and not their channel structure, which is a good approximation for a large number of interference but cannot reflect the impact of intelligent receivers, e.g. performing interference mitigation.

2.1.3 System Level Methodology for Next Generation Broadband Wireless Systems

One of the major difficulties in system-level simulations is the complexity involved in characterising the performance of the radio links between all terminals and access points. Identifying the right balance on the trade-off between complexity and accuracy is a challenging task, in a broadband, multi-antenna deployment with large number of resource elements to be managed (e.g. subcarriers, spatial channels) and the implementation of fast scheduling (in time, frequency, and/or space domain), fast link adaptation in form of fast power control and adaptive modulation and coding (AMC), or other advanced schemes such as Hybrid Automatic Repeat Request (HARQ) to be performed.

As part of their ongoing work on Smart Antenna systems optimisation, the ACE partners have addressed this challenge building on their previous expertise and guided by the identified knowledge gaps.

2.1.3.1 An approach suitable for multi-carrier, multi-antenna systems

In system level simulations, a common approach is to determine a SNR value that is translated into a block error rate using a look-up table based on earlier link level simulations. However, when simulating future generation systems involving wideband frequency selective channels and multiple antennas, the resulting block error rate does not depend on a single SNR value but on a large set of SNR values, one for each subcarrier and spatial subchannel. Since many systems, such as IEEE 802.11a,g and HIPERLAN/II use OFDM with channel coding across all subcarriers, it is difficult to map the large vector of SNR values to a single block error rate. One approach to handle this complexity is proposed in [12], where the full vector of SNR values is first reduced to two parameters, the empirical mean and standard deviation of the SNR across all subchannels. The block error rate estimate is then determined from a 2-dimensional table, using these two parameters as the input. The same dimension reduction techniques may also be used, for example in algorithms for adaptive modulation.

2.1.3.2 The WINNER Project Approach

Within the framework of the IST-Project WINNER (Wireless World Initiative New Radio) [14] particular attention is placed on the identification, assessment, and comparison of multiple access schemes, resource allocation, and link adaptation strategies as well as multiple antenna techniques. To understand system and user performance under reasonable operating conditions in various deployment scenarios, system level evaluations are required.

In Figure 6, a schematic diagram of a basic dynamic system level simulator is depicted. In general, two kinds of link models are required, a link measurement model, which models the measurements used for link adaptation and resource allocation in addition to a link quality model which determines the PER given a certain resource assignment and signal processing. Both models are related as they provide figures for performance prediction. Measurement models, however, are closely related to a specific system realization, whereas quality models are general enough to cover different multiple access strategies and transceiver realizations. It should also be possible to derive the parameters of such a model from a limited number of link level evaluations. This means that the model should ideally cover channel and interference conditions as well as modulation waveforms different from those used for training the model. In order to identify appropriate approaches to be used within the WINNER project, different link quality models were assessed.

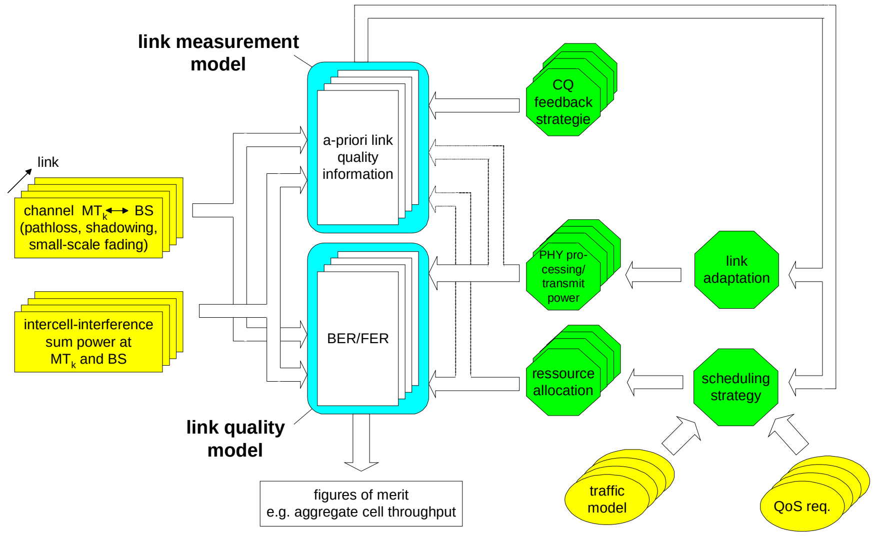

Figure 6: Example block diagram of system simulations (source WINNER, [13],[14])

Traditionally, the performance of the radio links has been evaluated in terms of the packet error rate as a function of signal-to-interference plus noise ratio (SINR), averaged over all channel realizations of one specific channel model. PER versus average SINR performance has therefore been used as the interface between the link- and system-level simulators. This may be adequate as long as every transmitted packet encounters similar channel statistics, which implies very large packet sizes/coding blocks with respect to the channel coherence time. But in case of data-centric radio networks, this condition is generally not fulfilled. Consequently, assessing the performance of fast resource scheduling and fast link adaptation in system level simulations requires a more accurate link quality model accounting for the instantaneous channel conditions.

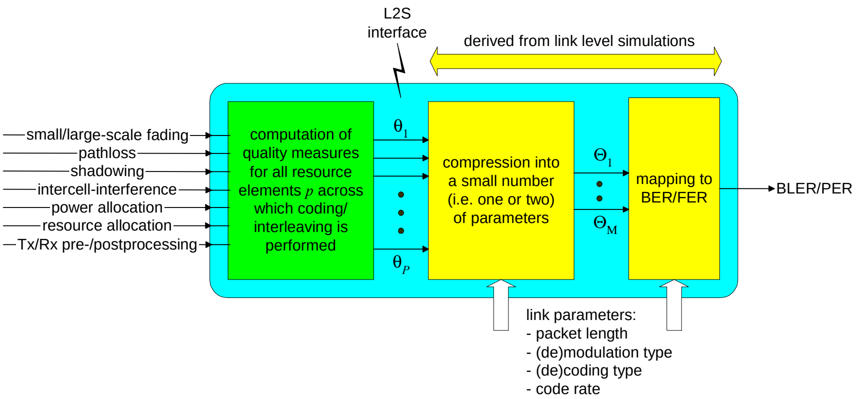

Figure 7: Potential realization of a link quality model (source WINNER, [13],[14])

A generic modelling approach that takes the instantaneous channel and interference characteristics into account is depicted in Figure 7. Many proposals found in the literature fall into that category. Once the scheduler has determined what resources are allocated to which users at what power level, the individual effective (MIMO) channels including pathloss, shadowing, small- (and large) scale fading as well as intercell interference are computed. From these values, a set of (possibly vector valued) quality measures is derived for all resource elements covered by a single codeword taking the actual spatial-temporal-spectral Tx/Rx pre- and post-processing into account. Since the number of resource elements can be very large (e.g. MIMO-OFDMA) and subsequent multidimensional mapping to PER is not feasible, some compression must be applied before mapping the compressed values to the PER.

The models proposed in [15][23] employ the raw bit error probability as quality measure whereas [17]–[20] use the post-receiver processing SINR instead. In any case, the computation of quality measures may be regarded as modulator/demodulator model (including equalization) whereas the compression and mapping to PER reflect the decoder behaviour. Such a split between demodulator and decoder is also considered in [15], [19], [23] and is general enough to cover systems including CDMA, OFDM and combinations thereof as well as various linear single- and multiple antenna transceiver designs by proper calculation of post-receiver SINRs.

Another alternative is to calculate the MIMO capacity for Gaussian signalling or the cut-off rate for the used modulation as proposed in [22]. A distinguishing factor compared to the SINR approach is that these metrics already provide a sum over the spatial dimension. For certain cases, such as the single antenna case, these metrics can be viewed as equivalent to the SINR metric.

In order to obtain a quality model of reduced complexity and training effort, we focus on a one-dimensional mapping between a so-called effective SINR and the PER. The corresponding mapping curve can be either that of the AWGN channel, i.e. the case for which all resource elements have the same quality measure, or an artificially created mapping function. It is then possible to cast the compression functions of the models proposed in [18][19] as well of those proposed in [22] (for the single antenna case) in the form

$$\mathrm{SINR}_{\mathrm{eff}} = \alpha_1 I^{-1}\left(\frac{1}{P}\sum_{p=1}^{P} I\left(\frac{1}{\alpha_2}\mathrm{SINR}_p\right)\right) \quad (1)$$

where α_1 and α_2 are model parameters and the SINR_{eff} corresponds to the parameters resulting form compression and SINR_p are the set of parameters to be compressed.

Four potential candidates for the selection of function *I*() have been considered in WINNER [1]:

- capacity effective SINR metric (CESM)
- exponential effective SINR metric (EESM)
- mutual information effective SINR metric (MIESM) and
- logarithmic effective SINR metric (LESM)

Validation results on the proposed quality model and mapping functions were provided in order to demonstrate the training and validation of the interface for the single antenna and a number of spatial processing techniques.

The MIESM was found to achieve high packet error rate (PER) prediction accuracy in case of resource specific adaptive modulation and in case of different spatial processing techniques as multi-user beamforming, space-time block coding and multiplexing. It was therefore chosen as the initial preferred model for all system simulations within the WINNER project.

The complexity of the proposed model may be challenging and decimation in time and frequency need to be considered.

2.1.3.3 The 4More Approach

In the 4MORE project [29] EESM was the methodology selected. As pointed out previously EESM is based on frequency channel value obtained at the reception side. Let *k* stand for the sub-carrier index, and let H_k stand for the channel frequency response power on each sub-carrier. Finally, we define the following quantity standing for the SINR on each sub-carrier where G_k stands for the geometry factor: $\gamma_k = p\overline{G_k}H_k$. The mapping function considers the whole code word sent over *N* sub-carriers:

$$EESM = -\beta \ln\left(\frac{1}{N}\sum_{k=0}^{N-1}\exp\left(-\frac{\gamma_k}{\beta}\right)\right) \quad (2)$$

where β is a parameter depending on the MCS (Modulation and Coding Scheme) used.

When considering the channel constant over the TTI duration, the summation in equation (2) can be done only over the system sub-carriers (N_u), which reduces the calculation burden. Another simplification can be done when considering the channel constant on a set of adjacent sub-carriers (which is the hypothesis made concerning 4MORE MC-CDMA system), the summation can be realized over N_u / SF where *SF* is the spreading factor.

(Remark: in case of spreading within 4MORE context, the minimal sub-carriers sub-set size is equal to the spreading factor since the interface granularity is at symbol level and not chip level.)

In fact one of the greatest challenges in performing end-to-end simulations for wireless networks lies in the integration of simulators that work with very different time scales, and use different approaches for simulation, i.e. system or network level simulators are usually event driven while at the physical layer the most common approach is to perform time-driven simulations. In the conventional approach to partition the problem simulations performed at the upper layers rely on abstract models to represent the lower layers as pointed out in the previous sections concerning the definition of a single or at least a reduced set of parameters to represent the physical layer behaviour when performing system level simulations. The accuracy of such an approach is obviously linked to the reliability of the models that are used to represent the lower layers. This may be insufficient for optimization of wireless systems, because on one hand due to randomness and dynamic nature of the physical environment it may be difficult to derive abstract models that encompass all effects that are relevant for the upper layers, and on the other hand because with cross-layer designs, radios will be "reactive" to the environment. However a full integration of all the aspects would be computationally prohibitive and would have to resolve inconsistencies originating from time-driven and event-driven schedulers (i.e. take into account the mechanisms through which time progress is achieved). We can therefore point out two main issues in the quest of end-to-end wireless simulators:

- A first one that be classified as a telecommunication problem and is related to the specification of accurate abstract models which was the solution targeted in the WINNER and 4MORE projects.
- A second one that fits in the category of software engineering, which relates to the efficient integration of simulators operating at different layers and using different time scales.

To overcome the limitations of the first approach, some solutions rely on the development of API's that interface with the real world, and namely in the initiatives that combine software simulators with interfaces to the real world have been reported (e.g. [30]), while at the European level and within the scope of the FP5 IST MATRICE project [31], and IP interface that collects IPv6 data to be used in the system simulations has been developed which is currently improved under the ACE framework [32].

Concerning the second point, there have been several proposals, some of them involving distributed computations (e.g. [33]), and others integrating the PHY layer and network layer simulators but using some kind of caching to store the PHY layer results and then to only invoke PHY layer procedures when events occur for which no similar behaviour has been observed and recorded in the past [34].

2.1.4 Outcome of Joint Research and Future Actions

The main outcome of the joint research performed during the first phase of ACE in the framework of the System Level Strategies for Smart Antenna Networks can be summarised as follows:

- Assessment of the state of the art in the area of system level methodology;
- Identification of the requirements and critical parameters particular to the case of multiple antenna networks;
- Identification of the open issues, challenges and knowledge gaps;
- Definition of a common approach to address the open issues/challenges associated with a system level methodology suitable for next generation broadband, multi-antenna networks;
- The above common approach has been implemented and evaluated in the framework of several activities the ACE partners are currently participating (e.g. other research projects) and the results produced therein have been disseminated internally and analysed within ACE.

In the context of ACE2, the partners plan to continue the above-described activities. In an effort to further refine the common system level methodology approach and optimise its applicability in terms of striking the right balance between computational complexity and accuracy, the partners aim at investigating possible approximation options for different sets of assumptions and scenarios.

2.2 Cross Layer Smart Antenna Systems Optimisation Networks

Nowadays, layering is the dominating design methodology of communication protocol stacks. An essential feature of the layering principle is layer-independence (modularity), which represents the classical engineering approach to solve complex problems.

However future generation networks including wireless are expected to provide reliable and highly variable QoS dictated by a large set of applications foreseen. The strict layering approach presents significant limitations to achieve this goal, especially when it comes to wireless communications.

2.2.1 Cross-layer vs. layered system design

Wireless networks are characterized by a dynamic topology (users move around, also enter and leave); the links exhibit a time-varying quality due to fading, shadowing, in addition to multiuser interference. To cope with this variability of the wireless channel, techniques have been developed either at the physical and MAC layers. With respect to the physical layer the adaptation to the channel characteristics can resort to adaptive transmission techniques (e.g. [35] and references therein) that go well beyond the conventional adaptation of transmitted power, while at the Medium Access Control (MAC) layer this resorts to appropriate scheduling [36] or sophisticated resource allocation algorithms that try to minimize the number of channels needed to accommodate users (e.g. [37] and references therein). The main shortcoming of the strictly based PHY layer approaches is that they do not take into account the impact on the upper layers, while the main shortcoming of strict layering MAC layer based schemes is that they are based on "hard" channels, i.e. they use a very limited information from the physical layer. If spectrum or other radio resources (power,…) usage is at a premium it is expectable that a more efficient management could be done if cooperation is considered between the MAC and PHY layers, namely by using at the MAC layer a richer set of physical (PHY) layer parameters. This is particularly true in MIMO (Multiple-Input Multiple-Output) systems, where the existence of SDMA at the physical layer raises significant issues at the upper layers and whose impact is significantly different according to the access scheme. In fact in SISO wireless systems, the radio resources (time slots or frequency slots) either in the TDMA / FDMA access schemes can be considered without significant error for well-designed systems as orthogonal. Even with CDMA schemes, the codes are designed to be orthogonal or quasi-orthogonal. Although transmission through dispersive channels may lead to the break of orthogonality, the departure from orthogonality may be moderate at least for low dispersion wireless channels, and thus from a layer 2 viewpoint it is not unreasonable to consider that the radio resources (codes, time-slots or frequency-slots) provided the PHY layer are available on an ON-OFF basis. The situation changes radically when considering the spatial dimension brought by the use of MIMO. Unlike the other types of radio resources (frequency-slots, time-slots, codes) this new one cannot be considered as a set of orthogonal or quasi-orthogonal items, and therefore considerable inefficiencies are to be expected if from the viewpoint of the MAC layer following the conventional strict layering approach the PHY layer is viewed as providing a set of "hard" (ON-OFF) bit pipes. Such a situation calls for a joint design involving cooperation between the two layers, violating the modularity and independence inherent to the strict layering approach.

Although the need or convenience to break the strict layering approach to reduce inefficiencies in wireless networks comes from the dynamic and random nature of the physical channel, and then the first choice when considering a cross or joint layer design is to look at the layer immediately beyond, this impacts higher layers too and the principles can be extended by using cross-information between the PHY and network or transport layers. For example certain routing protocols require that nodes broadcast control messages to all neighbours and wait for all of them to reply. In wireless networks, this imposes a tremendous strain on the medium access layer. Also, routing protocols tend to treat all neighbours as equally accessible although in reality those that lie on the fringes of the communication range of the node are much more susceptible to interference and should be avoided, as they represent a greater challenge to the medium access control layer. In other words, it is very important that the designers of the routing protocol of a system are aware of the limitations of the MAC protocol of that system, and vice versa.

2.2.1.1 Identification and exchange of cross-layer information (CLI)

A cross-layer architecture encompasses an additional complexity relatively to a strictly layered one, due to the fact that additional information besides the one that defines the basic service provided by the layer has to be exchanged. This need to exchange additional cross-layer information (CLI) leads to two fundamental questions

1) What information should be exchanged across protocol layers and, how frequently should this exchange take place?
2) What are the adequate / efficient procedures to exchange this information?

Since a cross-layer design is by definition a departure from a rule based procedure defined in a strict layering approach, there is no universal answer to either questions 1) and 2) and basically the answer to 1) depend on the specific algorithm that at a given layer make use of information from another one, while the answer to 2) will also depend on several algorithm dependent aspects (centralized vs. distributed) and on the specific systems architecture.

Although there is not a single cross-layer architecture, an attempt to *question 1)* can be made by considering the type of information in a broad sense that can be used at a given layer. In general it is possible to distinguish *from low to upper layers* five types of potentially useful information flows:

- PHY to MAC: Information from the physical layer such as interference level, multi-packet reception capabilities, etc, can be passed to MAC functionalities in order to improve collision resolution [38].
- PHY to DLC: Channel State Information (CSI) to provide side information to enhance link reliability or throughput, namely by advanced packet scheduling [39];
- PHY to Network: CSI such as data rate over the air, achievable throughput, etc., can be used to improve the routing process.
- DLC to transport: Link quality measures can provide a means to improve transport layer protocols such as TCP [40].

Alternatively, the parameters from the higher layers related to the QoS requirements for a given application, (e.g. tolerable delay, max-min allowable bit rate, BER/FER requirements, …) may be made available to the lower layers.

From what was mentioned above, and since the cross-layer design approach to minimize inefficiencies in wireless networks was mainly motivated by the dynamic underlying nature of the wireless channel, it turns out that CSI is the more important type of information from the lower layer that is needed for the upper layers. This involves the problems of *CSI availability* and *CSI requirements* from the upper layers.

Concerning the *requirements*, this will depend on the specific algorithms to be implemented at the MAC or upper layers, and although there is no theoretical impeachment for MAC or upper layer algorithms to use the full CSI, generally much less information is required: the most obvious one that will be needed is the SINR and propagation loss [41], while for MIMO systems a reduced number of parameters related to the spatial characteristics, like the AoA (angle of arrival), or the condition number of the spatial signatures [42] is necessarily sufficient for the current proposals of MAC and routing algorithms employing PHY layer information.

Of a different nature is the problem of CSI availability. The issues are quite different depending on the fact of where is CSI needed: either at the receiver or the transmitter. For a functionality at the receive side, the CSI is generally available from the channel estimation unit of the physical layer and the problem will be the one of signalling this information through intermediate layers. For a functionality at the transmit side (e.g. scheduling), the problem is, in general, more involved. In TDD systems and thanks to channel reciprocity principles, it is possible to use the channel estimates of the receiving link for the transmitting functions. This is however only valid up to a certain extent: due to the variability of the wireless channel, if the delay between the receiving and transmitting slots is higher than the coherence time of the channel (which may be common with high speed mobiles) the CSI is not reliable and then one has to resort to long-term statistics or to a reduced set of parameters that do not show such an high variability (e.g. AoA). Even with low speeds one may have problems if for example considering the UL-DL architecture of cellular networks, different access schemes and data formats are employed in the two links. With FDD systems the problem is further aggravated since in such a case one cannot make use of reciprocity and then feedback channels are needed. For the overhead to be small, the number of parameters to be transmitted must be small (but sufficient) and there is some ongoing work on this topic [43][44].

Considering now the answer to *question (2)*, we can identify two different problems

- Intra-node, inter-layer signalling
- Inter-node signalling and distribution of relevant parameters for cross-layer operation

For *intra-node* inter-layer signalling and transport of CLI, there are essentially four methods [45]:

- Packet Headers. In IPv6, optional Network-Layer information can be encoded in additional headers where the CLI can then be encapsulated. This method makes use of IP data packets as in-band message carriers with no need to use a dedicated internal message protocol.
- ICMP Messages. ICMP (Internet Control Message Protocol, [46] for IPv4, [47] for IPv6) is a widely deployed signalling protocol in IP-based networks, which can be an alternative to convey the interlayer CLI needed.
- Network Service. In [48], a specific access network service called Wireless Channel Information (WCI) was proposed. In this scheme, channel and link states from Physical Layer and Link Layer are gathered, abstracted and managed by third parties, the distributed WCI servers. Interested applications then access to the WCI for their required parameters from the lowest two layers.
- Local Profiles. In [49], local profiles are used to store periodically updating information. Cross-layer information is abstracted from each necessary layer respectively and stored in separate profiles. Other interested layer(s) can then select the profile(s) to fetch the desired information.

Of course, system-specific signalling protocols can also be used in order to convey CLI to functionalities residing in other layers in the local stack.

The second problem of *inter-node* distribution of CLI, which is of crucial importance not only for the implementation of distributed algorithms, but also for centralized ones, where although the resources can be assigned in a central point there is a need to distribute the assignment map. Although there is no specification of any universal architecture, and different solutions will probably arise according to the system considered, the inter-node distribution of CLI and resource map assignment will probably rely on some kind of broadcast channel, either differentiated by codes or using specific time-slots.

2.2.1.2 Protocol enhancement via cross-layering

In general, cross layer design involves five key layers in the overall protocol stack, namely, application layer, transport-layer, network layer, medium access control (MAC) layer and physical layer.

At the application layer, a media server can track packet losses and adjust media source rate accordingly [36][37]. To reduce information loss, the media server can employ packet FEC (forward error correct coding) and unequal error protection.

At the transport layer, several cross-layer approaches, such as EBSN [38] , snoop [39] and freeze TCP [40], have been proposed as TCP alternatives to distinguish congestion loss from non-congestion loss and invoke different flow control mechanisms.

At the link and network layers, the persistence level of the MAC layer ARQ mechanism should adapt to each application's latency and reliability requirements, while the link layer scheduler allocates radio resources to various packet flows based on their QoS priorities [41]. In other words, the scheduling process consists of partitioning limited resources among a set of users or connections. In a wireless context, if the scheduler has, in addition, access the channel state information (SNR, capacity, etc) associated to the competing users, it can increase dramatically the performance of the system with respect to ignoring the CSI.

2.2.1.3 On-going projects in the field

At present time, a very limited number of EC-funded R&D projects deal with the study of cross-layer interactions. Despite the significant gains that CL interaction could bring into future wireless communication systems, research in CL as addressed by those projects does not constitute the core topic but some side contributions in a more generic context.

To start with, the objective of 4MORE (4G MC-CDMA Multiple-antenna system On chip for Radio Enhancements, IST-507039) is to research, develop, integrate, and validate a cost effective, low power System on Chip (SoC) solution for multi-antenna MC-CDMA mobile terminals, based on joint optimisation of L1 and L2 functions. Most of the work deals with the MC-CDMA signalling physical layer but, also, it is objective of the project to consider enhanced MAC schemes that make use of rich PHY layer information. On the other hand, the aim of PHOENIX project (Jointly optimising multimedia transmission in IP based wireless networks, IST-001812) is to develop a scheme offering the possibility to let the application world (source coding, ciphering) and the transmission world (channel coding, modulation) to talk to each other over an IPv6 protocol stack (network world), so that they can jointly develop an end-to-end optimised wireless communication link. According to this definition, the main focus of the project is the joint design of source and channel coding strategies. However, a number of issues are still left aside: scheduling, incorporation of MIMO systems, PHY-layer enhanced routing, etc.

As for major projects overseas, one should point out the MIT μ-AMPS project: (http://www-mtl.mit.edu/research/icsystems/uamps/). However, the application (sensor networks) and targets (energy minimization) of this project are somewhat different from the ones most partners in ACE (cellular networks, WLANs, WPANS) but it aims also to explore cross-layer information in order to design an efficient protocol stack for wireless multisensors. Also, there is the SNRC Project *Cross-Layer Design of Ad-hoc Wireless Networks for Real-Time Media* where a new cross-layer framework for design of ad-hoc wireless networks to support delay-critical applications, such as conversational voice or real-time video is proposed. The framework incorporates adaptation across all layers of the protocol stack to leverage the flexibility offered by joint optimization of design parameters.

2.2.2 MAC schemes

The design of MAC protocols has been traditionally separated from that of the PHY layer. From a MAC layer point of view, the PHY layer (together with the channel) is commonly modelled in such a way that the success or failure of a packet transmission only depends on the number of users transmitting simultaneously, i.e., it is considered that a packet is received error free when only one user transmits.

This simplification of the PHY layer is known as the collision model. The collision model is both, pessimistic and optimistic. Pessimistic because it does not account for the possibility that packets may be successfully demodulated even in the presence of concurrent transmissions and optimistic because it does not account for channel effects such as channel fading. Although this model has been considered valid in wired and/or single user communication systems, recent advances in signal processing and multi-user communications make the collision model too simplistic and no longer appropriate for the characterization of the PHY layer properties.

Particularly, with the aim of increasing system performance, the use of antenna arrays either at the transmitter, at the receiver or at both sides of the communication link can provide significant benefits in terms of SNR gains, multiple access interference (MAI) reductions or multiple packet reception capabilities that should be taken into account by a MAC designer.

2.2.2.1 Review of MAC schemes for SISO channels

The most broadly known MAC protocol is probably the ALOHA protocol. The ALOHA protocol is a random access protocol developed by Abramson [50] in the 1970's that is based in a very simple but yet elegant idea: Transmit when the terminal has a packet and enter a random back-off procedure (retransmission probability) if the transmission is not successful. Under the consideration of the collision model, the back-off procedure allows to randomly split in time retransmission of collided packets and hence, to decrease the probability of collision.

Slotted ALOHA is a variation by Roberts [51] of the original ALOHA protocol to further reduce the probability of collision. Particularly, Roberts proposed to divide the time axis in slots and to restrict transmissions at the beginning of a time slot. In the case that each user chooses the retransmission probability so that the total offered load maximizes throughput (λ), then, the maximum achievable throughput is 0.36.

Another, more recent but also well-known and thoroughly analyzed MAC protocol, is the IEEE802.11 random access protocol [52]. This protocol was standardized as the MAC protocol for the wireless extension of Ethernet. The access method is based on the Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA). Since terminals are not able to hear the collision signal as in the wired world and to detect the collisions as in Carrier Sense Multiple Access / Collision Detection (CSMA/CD), they shall sense the medium prior to transmitting. Within CSMA/CA, two basic access methods are available, namely the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF).

DCF entity is mandatory and shall be implemented in each terminal. Since it is a type of CSMA/CA, if a terminal within the cell wants to transmit, it shall first sense the medium, and if it is not busy, transmission may proceed. The terminal has to ensure that medium is free before transmitting, but if the medium is busy, the terminal shall wait until the end of the current transmission. For that purpose, a Contention Window (CW) is implemented. That means that the terminal has to wait for a random number of time slots. After the transmission, each terminal has to receive a positive ACK, which means that the communication was successful. The main design goal of CSMA/CA is to reduce the probability of collision among several terminals that share the medium. Since after a busy medium situation there is a high probability of collision, a random backoff mechanism is needed. This random backoff eliminates the effect that all the terminals might want to transmit at the same time. Note that the backoff time is a random integer number of slot times. The integer number is the contention window and is upper and lower bounded, 255 and 0 respectively.

On the other hand, PCF method is only usable in network configurations, and it is optional. It uses a Point Coordinator (PC) that determines which terminal has the right to transmit. Basically, the PC is the polling master, and *asks* the terminals whether they have something to transmit.

2.2.2.2 Impact of Multiple Antennas on MAC protocols

Ward and Compton were the first authors to evaluate the performance of an adaptive antenna array in a slotted ALOHA packet radio system [53]. In [53], a set of mobile terminals transmit to a base station provided with a multiple-beam adaptive array. The multiple-beam adaptive array, allows the BS to receive multiple packets simultaneously. The mobile terminals transmit packets to the BS according to the slotted ALOHA protocol. Each packet is captured by a separate beam that nulls other contending packets. However, the success reception of a packet depends on i) the arrival angles of any interfering packets (because of the minimum angular separation between a desired and interfering packet), ii) The number of available beams (because a unique beam per packet is required) and iii) the total number of packets in the slot (because the number of possible nulls is limited). Ward and Compton based their analysis on a Markov chain model and on computing the success probabilities $P_s(i|j,K)$, where $P_s(i|j,K)$ is the probability of successfully receive i packets given that j packets are transmitted and that the BS has K beams. Similar approaches can be found in [54] and [55]. In [56], the authors propose a novel MAC protocol for a node in an ad-hoc network. In fact, Direction Of Arrival (DOA) information is used to place nulls where interference signals appear, so as to maximize the Signal to Interference and Noise Ratio (SINR) at the receiver. All these approaches are based of the idea of streerable arrays where beams and nulls are placed according to the estimated direction of arrival of the packets. Hence, these techniques are not optimal in very rich scattering and/or non line of sight environments, such as indoor environments. In such environments, interference cancelling receivers such as Zero Forcing, MMSE or V-Blast are needed. Characterizing the multiple access interference and its effects on throughput in such kind of receivers is a bit more complex and the optimal MAC design is the one able to reach the optimal trade-off between number of simultaneous transmissions and multiple-access interference. Some insight to that problem is given in [57].

In order to improve the bottleneck that might occur in ad-hoc networks, the authors in [59] also propose the use of a SDMA scheme. A directional link among several mobiles allows a higher number of communications to take place at the same time. The authors, and references therein, use a directional RTS/CTS handshake mechanism, thus they *block* a certain space instead of the whole space. Moreover, transmissions to several users can occur at the same time, as it is done in [60] for 802.11 networks. In [59] all this is illustrated by the detailed explanation of a MAC protocol. Similarly, in [61] the authors exploit the use of multiple antennas in the DCF operation of 802.11. Basically, omnidirectional RTS/CTS are used to initiate then array-mode data packet transmission. In fact, a lower power can be used while maintaining a sufficient link margin. Results are provided in order to show the delay performance. A similar idea is proposed in [62], where, again, a directional CSMA/CA protocol is used for the application in 802.11. In [63], the authors propose an alternative to solve the problem in the traditional RTS/CTS handshake mechanism, for which multiple antennas can be very useful. Again, reference [64] proposes the use of directional RTS and CTS messages.

2.2.3 Packet scheduling in MIMO systems

Efficient packet scheduling schemes are required to manage the users access to the resources according to the instantaneous traffic requirement and the channel condition they are experiencing.

The scheduling algorithms commonly used in wired networks [65] could be in principle used in mobile systems but the efficiency would be for most scenarios rather poor. In fact in wired networks, one can assume in most cases time-invariant physical links and therefore a scheduling policy based only on the service requirements or relative priorities and independent of specific physical layer parameters can be meaningful. However, the situation is totally different in wireless networks [66]: the topology is dynamic (user moves around, also enter and leave), the links are potentially less stable and prone to generating errors in bursts, strict constrains in terms of transmitted power apply (in particular, for mobile hosts), link characteristics are time-varying and location-dependent, and one may have wireless links fully connected but with different link Signal to Interference Ratio (SIR), or for the same link, different SIRs as time evolves, etc.

As a conclusion, a scheduling policy inherited from the wired world and ignoring the dynamic nature of the channel would therefore lead to a very inefficient resource usage (e.g. a high priority service would be scheduled even if its channel was very bad, leading to an unnecessary use of resources).

Information-theoretic models for the Broadcast (BC, i.e., downlink) and the Multiple Access (MAC, i.e., uplink) channels exist. In a broadcast channel, a multi-antenna access point sends common information to several terminals, whereas the reverse problem in the uplink consists of several terminals transmitting information to the access point. It has been recently shown that multiple antennas increase the capacity of a point-to-point communication link with M transmit antennas and N receive antennas as min(M,N) under independent assumptions of the fading and the noise [67]. In a multi-user system, the sum-rate capacity and, in fact, the whole capacity region[1] can be attained via Dirty Paper Coding (DPC) [68]. As pointed out in [69] and [70], even though the sum rate *capacity* of a MIMO BC using DPC can be stated as a convex problem using duality, the sum-rate *throughput* of beamforming cannot be written as a convex optimization problem, so it is computationally intensive to compare the throughput of DPC and beamforming. Extending [71], it is proven in [72] that the gain of DPC over simpler time-sharing approaches is bounded by min(M/N, n), where n denotes the number of users, which tends to infinity. The scaling law of the sum rate is the same for beamforming and DPC when M is fixed and n goes to infinity, but the particular multiplying constant is lower for the beamforming.

In [73], the dirty paper rate region is shown to be equal to the capacity region of the dual MIMO multiple-access channel (MAC or uplink) with sum power constraint P_T. The dual uplink is formed by reversing the roles of the transmitters and the receivers. Regarding beamforming, it is shown in [74] that transmitter beamforming for the broadcast channel without pre-coding is dual to receiver beamforming for the dual MAC without successive interference cancellation.

Dirty Paper Coding is difficult to implement in practice and, thus, current systems such as Qualcomm's High Data Rate (HDR) system implement opportunistic communications instead, where the user with best channel is scheduled at any time [75]. According to [76], the expression for the sum rate capacity is not a concave function of the positive semi-definite covariance matrices. Therefore, is numerically and analytically difficult to deal with.

As a result, the most straightforward approach to CSI-aware (i.e. cross-layer) scheduling amounts to ordering the users according to the SIR of the respective channel. This represents the opposite of the scheduling policies for wired networks in the sense that now only the physical layer information is used to schedule packets, and fits in what is generally termed as opportunistic scheduling [36][75] which exploits the so-called multi-user diversity. Such an approach gives good results when traffic characteristics are homogeneous and applications are relatively insensitive to packet delay since, ultimately, *max-SIR* (i.e. *greedy*) scheduling is equivalent to throughput maximization [41]. However if packet delay is an issue, or if we have multiple services have different requirements, this may lead to inefficiencies since the users with the best channels tend to monopolize system resources. These considerations reveal two important problems related to spatial scheduling: (1) what kind of cross-layer information should be exchanged and (2) how can we design a *fair* scheduler. These two fundamental questions will be addressed in the subsequent sections.

[1] The achievable region for the Gaussian BC is defined as the convex hull of the union of all such rate vectors over all positive definite covariance matrices that satisfy the power constraint [73]. Note that the user ordering is crucial in this problem.

2.2.3.1 CL information and packet scheduling

When designing scheduling strategies, it is often assumed that perfect channel state information is available at the transmit side (CSIT). This assumption is, in general, far from being realistic because of the errors occurring in the feedback channel, quantization and delay effects and, also, because of the necessarily low bandwidth that can be allocated to such feedback channels. This can be even worse when any of the communication edges features multiple antennas (i.e. SIMO, MISO, MIMO configurations) since the amount of CSI grows linearly in the product of the number of sensors, and/or in systems with a high number of users with shared return channels. In those cases, one should resort to partial CSI being conveyed at an *adequate* rate over feedback channels. Still, the design of *robust* scheduling algorithms on the basis of partial CSIT information is advisable.

When multiple antennas come into play, the ergodic or instantaneous channel capacity constitutes a natural extension to the SNIR information that is usually exchanged in SISO contexts. However, a plethora of alternative measures exist: noise enhancement factors introduced by detection schemes, equivalent SNIR at the output of transmit or receive beamformer, largest matrix determinant, rank, condition number, etc. Some scheduling schemes derived on the basis of such information were analyzed and compared in [77].

In addition, proposals have been made for scheduling algorithms that use the parameters from the physical layer *but also* take intro account QoS parameters from the upper layers. In [79] the prioritisation function to schedule the packets, considered a function that weighted parameters from the PHY layer, namely the SIR and the number of attempted retransmissions considering Chase combining at the reception, and the allowable delay for the service considered and parameters related to the service requirements. Other approaches, trying to equalize the average throughput to provide in doing so some kind of fairness have been proposed either for single or multi-antenna systems [80][81], however they still fit in the category of PHY layer based scheduling algorithms, since the fairness is something that is a consequence of the algorithm and not a QoS input from the upper layers. Furthermore they still implicitly consider homogeneous services, from which the fairness requirement arises. The joint selection of the modulation and coding scheme together with the scheduling has also been considered [39].

2.2.3.2 Fairness issues

Within the context of packet scheduling, there is a fundamental trade-off between optimizing overall system performance and satisfying individual needs. For instance, maximizing cell throughput could result in a need to assign a very small fraction of the available bandwidth to users close to the cell boundaries, which could not be desirable. On the other hand, several scheduling strategies can be found in the literature, this leading to different interpretations of the *fairness* concept.

Round-robin (RR) approaches constitute a very simple solution to the scheduling problem. Essentially, users are selected for transmission in a sequential manner, that is, disregarding any kind of CSI information that could be available. In terms of fairness, each user gets an identical share of the available bandwidth but, at the system level, overall cell throughput could be improved by scheduling at each time instant the user experiencing *best* channel conditions. In [82], traditional round-robin schemes were enhanced (in a MIMO context) by conducting a SNIR-assisted group-wise mapping of users to transmit antennas. By doing so, each user gets a fraction of the on-air time (since each group does) and, simultaneously, overall cell throughout subject to some constraints is maximized.

Other fairness criteria such as *max-min*, *maximum sum*, or *proportional fair* can also be found in the literature. The so-called *max-min* criterion tries to optimize the worst-case situation, yielding solutions where resources are equally shared. On the other hand, *maximum sum* techniques are aimed at obtaining the optimum *mean* performance, which is usually translated into an uneven resource allocation, i.e. some users get a large amount of resources, whereas others get virtually nothing. Finally, with a *proportional fair* criterion, resources are allocated according to instantaneous conditions but, also, the average behaviour is taken into account. In other words, the user with a higher ratio between the instantaneous metric (e.g. SNIR , capacity or link throughput) and its mean over a pre-defined time interval is scheduled for transmission, that is, in an opportunistic fashion [81]. By doing so, all users get the same resource share over a long enough horizon. If long-term fairness is not an issue, one could resort to *max-SNIR* greedy schedulers where the user(s) experiencing the (absolute) best channel conditions are scheduled at any time. However, this clearly penalizes terminals experiencing lower mean SNIR conditions.

Following [81], a number of papers propose proportional fair scheduling algorithms for multi-user MIMO systems. The reader is referred, for instance, to [83] where the scheduling problem in the downlink is addressed with multiple-antenna in the terminals and the base station (BS). At the transmitter, all antennas are assigned to only one user out of those awaiting to be scheduled but, in order to induce fast fading and be fair with other users for all channel conditions (in particular, with slow fading), a weighting matrix is used at the transmitter side. The authors compare algorithm performance with equal-time scheduling where a water-filling strategy is applied to the scheduled user. Clearly, these two schemes differ in the amount of CSI required at the transmitter: full CSIT for the latter vs. no CSIT in the case of the opportunistic approach where, moreover, there is no need for the terminals to know that multiple antennas are available in the BS.

In [84], a MIMO system is studied in the uplink (i.e. MAC problem), where the BS is provided with multiple antennas in a context of single-antenna terminals. User detection in the uplink is conducted following a successive interference cancellation method in order to maximize sum-rate capacity with a restriction on the transmit power. As for the scheduling principle, a proportional fair scheduling mechanism is adopted. Note that exhaustive search is needed over users and the detection ordering. The authors claim this approach is applicable to IEEE 802.11 with only minor modifications.

In [85], the impact of path loss on the scheduling algorithms is investigated in a multi-cell 1xEV-DO environment. Performance exhibited by traditional scheduling algorithms such as Round-Robin, best SINR, etc is assessed along with that of *fair* algorithms where previous transmissions are penalized by a capacity metric. System-level computer simulations are used to investigate how individual average throughput is affected by mobile location within the cell. The results obtained reveal that mobile performance can be greatly affected by its positioning in the cell, but this greatly depends on factors such as the number of antennas at the receiver and the transmitter and, also, the scheduling method in use. The maximum SINR scheduling maximizes throughput at the expense of the poorer users. The overall throughput for proportional fairness scheduling is also considerably higher than that of round robin scheduling. Unlike maximum SINR, however, with proportional fairness, all mobiles benefit, irrespective of the quality of their link to the base station.

For an overview and implementation details of scheduling algorithms, please refer to [86]. For a theoretical framework to analyze multi-user communications in terms of fairness, see [87].

2.2.3.3 Scheduling and user mapping in the spatial domain

In a SISO multi-user system, it is well known that, the average cell throughput is maximized when in each time slot the user with better channel conditions is served [88]. However, if multiple antennas are available at the transmitter and/or the receiver, the number of degrees of freedom is larger and, thus, more sophisticated mapping strategies can be devised. Clearly, more than one sensor is needed at the receiver in order to allocate multiple data streams to a specific scheduled user.

In a MIMO context, a straightforward mapping strategy consists in allocating all the transmit antennas to one user at a time (e.g. [85]). However, we can do better by exploiting the corresponding spatial channels and scheduling several users in the same time slot. This extent is investigated in [89] in an opportunistic scheduling context and for two different detection methods (ML and ZF) being used in multiple-antenna terminals (the single-antenna case is addressed for instance in [77]. Both analytical and computer simulation results reveal that overall system capacity is improved when multiple users are scheduled simultaneously on the basis of capacity or SNIR measures. This work is extended in [90] where three scheduling approaches are compared: one user per time slot following a first-come first-served scheme, one user per time slot maximizing instantaneous channel capacity, multiple users per time slot (mapped into different transmit antennas) maximizing sum-rate capacity. Results are given in terms of throughput vs. delay curves and show that the multi-user strategy outperforms the single-user ones. In the previous examples, though, fairness among users in the system is not addressed at all (i.e. identical average SNIR and fast fading is assumed). Conversely, the authors in [91] introduce some fairness notions by scheduling users in groups under a CSI-assisted round-robin framework. *Within* each group, the mapping of users into different transmit antennas (exhaustive search needed) is given by the post-detection SNIR at the output of either ZF or MMSE receivers. Performance in both correlated and uncorrelated spatial channels is assessed in terms of ergodic and outage capacity as a function of the number of users and SNIR at the cell boundaries. Fairness issues are also taken into consideration in [83] where a random weighting matrix is used to compensate for slow-fading fluctuations (one user only per time slot).

In [77], some scheduling algorithms and transmissions strategies were investigated for the downlink of a cellular system, where a multi-antenna BS and single antenna users are considered. In the partial CSIT case, user terminals have perfect channel knowledge and feedback partial channel information to the scheduler. In particular, each user estimates the received SNIR for each BS transmit antenna and, then, feedbacks the maximum SNIR value and the corresponding antenna index to the BS. With that information, the BS chooses the best subset of users that maximizes the SNIR for each transmit antenna. Hence, a very simple scheduling structure is provided with that strategy, but due to each user has only one receive antenna, linear multi-user detection techniques cannot be used to separate the interfering signals (no spreading either) and therefore system performance is interference-limited. Multiple antennas can be used at the receive side to perform interference suppression with linear receivers [92].

On the other hand, with perfect CSIT, transmit beamforming can be used to combat multiple user interference. It was shown in [77] that the sum-rate capacity can be approached with reduced-complexity processing at the transmitter. In particular, it was considered zero-forcing transmit beamforming followed by waterfilling power allocation, and great improvement was achieved. Therefore, in a MIMO context, perfect CSIT is crucial in order to achieve improvements in terms of throughput by keeping simple scheduling techniques and reduced-complexity algorithms at the transmit and receive sides.

The combination of spatial scheduling with adaptive modulation and power allocation strategies deserves some attention, as well. Adaptive modulation issues are addressed in [93] where, for each spatial channel (given by the SVD decomposition) of the scheduled user, the modulation scheme providing the highest throughout under specific BER constraints is selected. In [78][95], waterfilling power allocation is conducted for the scheduled user(s).

2.2.3.4 Interaction with transmission queues and AMC

When designing advanced algorithms for the physical layer of modern communication systems, buffer size and queue length information are seldom taken into consideration. In general, the existence of infinite transmission buffers is assumed which, in fact, is not very realistic. Actually, an adequate interaction of, for instance, the available adaptive modulation methods, scheduling strategies or coding schemes with queues and buffers is highly desirable in order to minimize packet delay or, even, packet loss.

Reference [96] constitutes one of the first attempts to incorporate queue information from finite-length buffers into the overall design process. Within a context of a SISO single-link scenario, the authors exploit such information in order to maximize link throughput that, ultimately, depends both on the number of packets dropped in the wireless channel (because of inappropriate combination of rates/coding schemes) and, also, in full transmission buffers. Whenever the resulting data rate and packet error rate are too high, the probability that data packets will be dropped in the wireless channel increases. Conversely, if data rate is too low, packets will be dropped in the transmitter because of queuing overflows. Therefore, the optimal transmission modes are designed and triggered according to the extended parameter set including packet arrival rate, service time, required BER for modes, buffer size and actual channel state information. Buffers are modelled as finite-state machines.

Queuing information, though, can also be readily exploited in a multi-user MIMO context. Consider a MIMO-MAC system where a number of mobile stations (K) equipped with multiple antennas share the uplink channel to reach a multi-element base station. Also, assume that either a sum-power constraint or individual power constraints apply to such individual mobile users. It is well known [97] that, in order to maximize the sum of simultaneous achievable bit rates (i.e. sum-rate uplink capacity), one should determine a set of *transmit* covariance matrix for those *K* users. As for the *receiver*, the multi-user sum rate capacity can be achieved via a MMSE scheme with successive interference cancellation (SIC), this featuring lower complexity than its corresponding ML counterpart. To do so, though, the optimal detection order for SIC must be identified, as well.

In the MIMO-MAC scenario described above, the sum-rate capacity might be maximized at the expense of very low actual data rates for some uplink users. As a consequence, very long transmission queues could result for those mobile stations. In [98][99], Boche *et al* take those queue lengths into account and, instead, aim at maximizing a *weighted* sum-rate capacity expression (weighted by queue lengths). By doing so, it is shown that the corresponding *stability region* (i.e. the set of packet arrival rates to MSs for which transmission buffer lengths do not grow to infinity) is the largest possible. In this case, the optimal SIC order in the BS does not depend on channel propagation conditions but it is solely given by users' queue length. In other words, users with higher instantaneous queue lengths will be decoded last in order to take advantage of the lower intra-cell interference level from the lower number of remaining un-detected users (if any). As for the determination of the optimal transmit covariance matrix, it is shown in that is constitutes a convex optimisation problem and, therefore, the global maximum can be achieved regardless of the starting point by means of the so-called interior point methods.

A multiple-access communication system where scheduling takes into account queue states is also studied in [100] where a *Longer-Queue Higher-Rate* allocation strategy helps minimize packet delay by adaptively adjusting coding schemes to meet any given level of decoding error probability. A unified cross-layer analytical framework for broadcast channel is provided in [101], where controlled queuing systems maximum throughput subject to delay guarantees.

2.2.3.5 Computational complexity, feedback requirements and performance issues

Complexity is a key issue that should be carefully taken into account. Note, for instance, that many scheduling problems are NP-complete, thus suboptimal algorithms are totally adequate [102]. In general, as the number of users increases close-to-optimal solutions seem to be unfeasible, and better performance usually comes at the expense of complexity. [84] proposes three versions of the scheduling algorithm in decreasing degree of complexity. Again, more complexity yields better performance in terms of throughput vs SINR per user.

Apart from computational burden, one more issue in the scheduling process is that CSI for all active users should be made available to the resource manager in the Access Point (AP). In the literature, the AP is often assumed to have perfect CSI but this is clearly unrealistic, in particular for Frequency Division Duplex (FDD) systems, for which channel reciprocity assumptions do not hold. In large systems, it might also be difficult to know the channel state every single user, in particular when considering multi-dimensional scheduling. In order to solve this problem, the transmission probability (or resource requests) for each user can be a function of its own CSI [103][43]. This means that no resource requests will be made unless channel conditions do not exceed some pre-defined quality threshold. By doing so, the terminals cooperate with the AP in order to globally minimize the requirements on the feedback channel. In parallel, efficient feedback methods should be devised, so that terminals feed back a reduced number of CSI parameters (this issue becomes especially important in MIMO channels, where the number of parameters is high). An efficient implementation should consider the quantization of channel estimates, whereas in [104] the authors apply differential coding. The design of feedback channels has a direct impact in terms of goodput, since part of the available bit rate shall be devoted to them.

2.2.4 Multi-dimensional packet scheduling

Traditionally, communication systems allocate multiple users in one dimension only, namely, time for Time Division Multiple Access (TDMA), frequency for Frequency Division Multiple Access (FDMA), and space for Space Division Multiple Access (SDMA), as it is shown in Figure 8a. However, the need s in large wireless systems to provide data rates above 100 Mbit/s at a very high spectral efficiency can only be fulfilled if *fast* scheduling is conducted over a combination of the above-mentioned dimensions, i.e. using all available types of diversity (see Figure 8b). In this context, the use of antenna arrays allows to create parallel spatial sub-channels and, eventually, increase system capacity at the link layer.

Unfortunately, multi-dimensional scheduling means a dramatic increase not only the amount of CSI involved therein but also in terms of computational complexity. As a result, the problems to be solved are, in general, NP-complete [105] and the investigation in suboptimal solutions is mandatory.

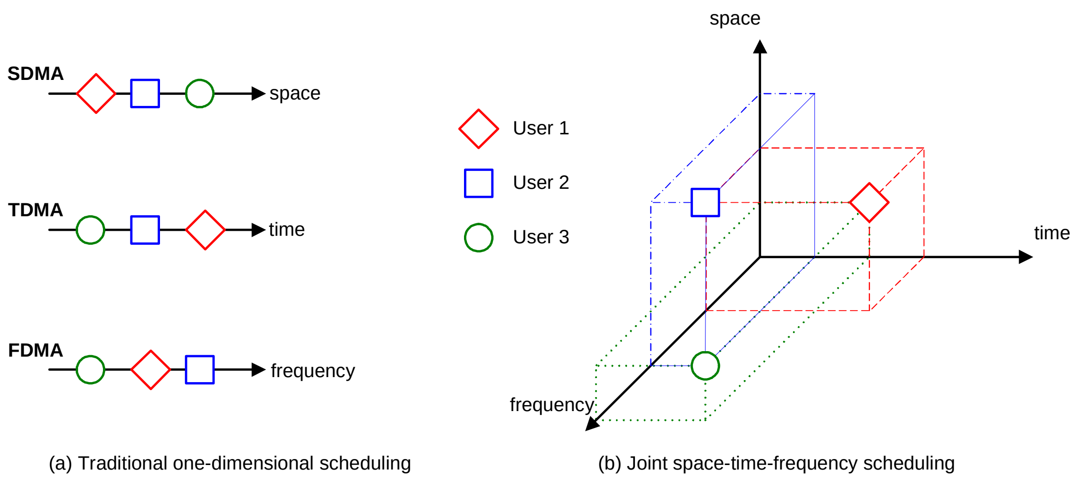

Figure 8: Traditional scheduling vs. advanced multi-dimensional scheduling

2.2.4.1 Space-Time scheduling

In [106], the space-time scheduling problem is addressed. The authors assume that terminals have a single antenna, whereas the AP is provided with Q antennas, so that users shall be divided into groups of Q users at most for simultaneous space-time transmission. Although optimal downlink beamforming solutions are well-known [107], space diversity can be exploited by a Zero Forcing (ZF) criterion, which provides simple closed-form solutions. Besides that, it creates orthogonal channels for the users belonging to the same group, i.e. there is no inner-group interference. If the minimization of the transmit power is chosen as a PHY cost function, the partition of users into groups within the scheduling is an NP-hard combinatorial problem. Therefore, close-to-optimal real-time solutions are found. The exploitation of multiple dimensions will lead to a high increase in capacity, but the optimum performance will be difficult to attain since real-time implementation is extremely important for scheduling techniques.

In [108], the authors deal with the problem of dynamic slot allocation in the uplink of an SDMA/TDMA system. The objective is to minimize the length of the frame, while ensuring a minimum Signal to Interference plus Noise Ratio (SINR). On the basis of graph theory it is shown that, even without bit allocation, the problem is an NP-complete. Consequently, the authors propose several heuristic slot allocation algorithms and design a maximum SINR beamformer, which is equivalent to the ZF criterion in the high SINR range. An extension is developed in [109], where a polling protocol is specified. In [110] the authors take the best fit strategy proposed in [108] and extend the algorithm to take into account several QoS parameters in addition to traditional SINR, namely, packet timeout and packet loss. Their heuristic approach sorts first the users by evaluating the QoS parameters, and then selects the users according to their spatial characteristics. Accordingly, in this paper the bit allocation is performed together with the scheduling.

Recent approaches to user selection include [111] and [112]. In the former, given a ZF beamforming criterion, the users are selected according to a variety of criterion. An equal proportional SNR mechanism is proposed, which attains an intermediate performance between two well-known techniques. On the other hand, in [112] the authors prove that with ZF transmit beamforming it is possible to attain a large fraction of the maximum sum capacity in a scenario with several users. On the other hand, several greedy algorithms are proposed in [102] to group the users into slots. Usually, more complexity yields better performance when the number of users increases.

2.2.4.2 Space-Frequency scheduling

Orthogonal Frequency Division Multiplexing (OFDM) is an attractive modulation for implementing multiuser diversity in the downlink [113][114]. With OFDM, frequency fading can be exploited in addition to the temporal fading and different users are scheduled in different time-frequency blocks.

Opportunistic beamforming uses multiple transmit antennas to increase the temporal fading rate of the individual users, by changing the random beamforming every transmission block [81]. This idea can be directly extended to OFDM by also changing the beamforming weights between the frequency blocks [115][116]. This increases the frequency fading rate of the users.

Multiuser diversity scheduling relies on fast measurements and feedback from all users. In an OFDM system with hundreds of sub-carriers, the feedback of measurements on all sub-carriers from all users can be unacceptably high. By grouping adjacent sub-carriers into clusters and feeding back measurement results only from the strongest clusters, the amount of feedback information can be greatly reduced with no significant loss in performance [115].

Opportunistic beamforming assumes no explicit channel state information at the transmitter. However, all users feed back some measurement information about the strongest clusters, conditioned on the current beamforming configuration. This can be used by an integrated scheduler and beamformer to increase the fairness of the system and/or to boost the total cell throughput [116].

Indeed, the addition of the frequency dimension is not an easy task. In this sense, in [113] the authors propose an SDMA-OFDM scheduling technique so that the users are assigned to subcarriers in order to maintain a minimum Quality of Service (QoS). By considering Bit Error Rate (BER) requirements, it is possible to perform the call admission control and an efficient management of resource requests.

As commented above, multiple antennas can be deployed on top of the dimension in order to serve several users simultaneously. Moreover, bit allocation can be performed to attain the maximum throughput of the system. Several approaches are given in [117] with several degrees of complexity. If a bit allocation is performed, a possible option is to use the same users and the same number of bits at adjacent subcarriers, which is related to the coherence grouping in [118] and references therein, where the focus is on beamforming.

2.2.5 Interaction with DLC schemes

It is widely acknowledged that adaptive modulation and coding techniques can further improve spectral efficiency by adjusting transmission parameters to time-varying channel conditions [119], in particular when applied to MIMO configurations [120]. Adaptive modulation schemes in combination with antenna selection strategies were introduced in e.g. [121][122]. By switching off transmit antennas elements unable to meet specific QoS requirements the overall interference level can be reduced and, thus, higher constellation sizes can be supported by the remaining ones. In general, antenna selection principles can be applied to MISO, SIMO or MIMO systems and can refer to the transmitter side, the receiver side or both.

One of the most popular antenna selection mechanisms that can be found in the literature is the so-called hybrid selection scheme. The goal of this strategy is to select a pre-determined number of active antennas out of a set of M transmit antennas maximizing a specific target function (such as channel capacity). Ultimately, this approach is aimed at increasing spatial diversity while reducing hardware costs since additional antenna elements are usually inexpensive with respect to RF chains. On the other hand, one could let the number of active transmit antennas vary from burst to burst, up to a total of M antennas. By doing so, antenna selection becomes an effective means of conducting rate adaptation.

Going into further detail, when multiple antenna elements are available at both link ends, there are three basic ways in which this can be exploited:

- Exploit the diversity effect, which means that transmit and receive diversity are used purely for link-quality improvement. All transmit antenna elements transmit streams of the same information. The antenna selection approach in this case is called “Hybrid-selection / Maximal Ratio Combining (HS-MRC)” or sometimes also “Generalized Selection Combining” (GSC) and apart from MIMO it can be employed to SIMO and MISO systems as well.
- Multiple elements at both link ends are used for “spatial multiplexing”. In this case, transmit antenna elements transmit different, independent symbol streams (or partially correlated streams), exploiting the formation of independent spatial communication channels. The antenna selection approach, here, is called “Hybrid-Selection/MIMO” (HS-MIMO).
- The communication system, to which antenna selection is applied, is a “Space-Time Coding” System. This means that Layered Space-Time Coding strategies are used in order to approach the theoretical capacities of a MIMO system (BLAST systems). In this case, independent (or partially correlated) symbol streams are transmitted from the transmit antenna elements too.

If multiple antennas are used for diversity purposes, three types of selection combining can be identified:

- **Maximal Ratio Combining (MRC):** The SNR of the optimal ratio combiner is the coherent sum of the SNIRs of each individual diversity branch.
- **Conventional Selection Combining (CSC)**: The CSC combiner selects the signal from that diversity branch with the largest instantaneous SNIR.
- **Generalized Selection combining (GSC) or Hybrid-Selection/MRC (HS-MRC)**: The GSC combiner chooses the L largest signals (instantaneous SNIRs) from the N total diversity branches and then combines them coherently.

As shown above, it is common practice to select the subset of transmit antennas according to PHY-layer related parameters (e.g. SNIR). However, we could do better by taken into account functionalities in the upper layers, that is, following a cross-layer approach. This extent will be studied in subsequent sections.

As far as the time framework for antenna selection, two different cases exist: :

- *‘Deterministic Antenna Selection’*: Sets of antenna elements are selected per channel instance (realization), with computation of optimal sets performed every time the channel changes.

- *'Statistical Antenna Selection'*: MIMO antenna sub-set selection is based on second-order channel statistics, when spatial multiplexing or space-time coding techniques are used over the wireless link.

2.2.5.1 CL-oriented vs. PHY-layer antenna selection

As for the selection criteria, it is common practice to select the subset of transmit antennas maximizing channel capacity [123][124]. A more detailed description of antenna selection based on CL oriented criteria can also be found in [125]. As a conclusion, one can observe that with antenna selection a capacity very close to that of the full-complexity system can be achieved as long as the number of the antennas selected is greater than or equal to the number of the transmitting antennas. To do so, though, the impulse response for a total of $M \cdot N$ equivalent SISO channels, has still to be estimated which could constitute a complex task by itself for large M and N. Alternatively, one could monitor the SNR on the receiving antennas. Simple hardware, such as signal (and interference) strength indicators, provides this information to the receiver without requiring any base-band processing. If the signal strength is averaged over a large number of MIMO symbols and the symbols on the transmitted antennas are independent, then this procedure is equivalent to the selection of the rows of with the highest Euclidian norm. An interesting point is the comparison between antenna selection criteria based on SNIR and those based on capacity. It is shown in [125] that only 50% of all channels realizations did the two selections agree with each other. This behaviour can be interpreted in geometric terms by the insights of [126], which showed that for the deterministic case (corresponding to one channel realization), the phase shifts between the antenna elements are the decisive factors for the capacity, and are far more important than instantaneous SNIR.

Such capacity-based approaches, though, do not exploit all the information available in specific system scenarios concerning the schemes and algorithms being used at the physical and link layers. However in practical communications systems, link quality is determined not only by data detection methods in the physical layer but, also, by the specific coding scheme being used, MAC/DLC functionalities in the link layer, or protocols in the upper layers of the protocol stack. In a packet-switched wireless communication system, all those constituent blocks should work together in order to attain the highest possible *throughput*, as opposed to the highest *data-rate*. Therefore, a transmit antenna selection criterion based on cross-layer designs, where the antenna subset that maximizes link layer *throughput* is selected [127], seems to be more appropriate rather than others exclusively based on physical layer parameters (such as channel capacity criteria). In particular, a packet-switched wireless network based in the V-BLAST architecture in combination with different Hybrid-ARQ strategies (Go Back N, Selective Repeat, N-SAW with chase combining) was analyzed in [128][129][130]. It was shown that, while maximizing channel capacity tends to use the maximum number of transmit antennas, different antenna configurations are selected by the throughput criterion according to channel conditions. The reason for that being that channel capacity does not take into account system characteristics (receiver structure, packet size, modulation scheme and H-ARQ strategy). Conversely, all the system parameters are taken into account in the throughput criterion and, accordingly, the maximum data-rate that minimizes the number of retransmissions is selected. For that reason, as soon as more efficient H-ARQ strategies (Selective Repeat or N-SAW with chase combining) are used the number of transmit antennas that the algorithm selects is higher (and so is the effective data-rate), due to the fact that packet retransmissions seldom occur. Furthermore, when adopting a throughput-based criterion, the integration of an adaptive modulation schemes with the AS strategy comes in a very natural way [131], this rendering unnecessary separate optimizations (often resorting to heuristic criteria).

2.2.5.2 Rate adaptation via STC and Spatial multiplexing

Essentially, MIMO schemes can provide either diversity or spatial multiplexing gain. Most of current MIMO research is focused on maximizing only one type of gain but, recently, studies that combine both types of gains have appeared in the literature [132].

In [133], a system based on the switching between multiplexing and diversity is proposed. According to the instantaneous channels conditions, the transmission mode is switched in order to minimize the symbol error rate. Since, in wireless communication schemes, CSI is usually only known at the receiver, a feedback channel is required to inform the transmitter about the selected mode (but only one bit). For a fixed data rate, it was shown that choosing the best mode for a given channel realization, better results can be obtained than with either diversity or spatial multiplexing alone.

In [134] a switching mechanism between diversity and multiplexing was also proposed. Nevertheless, in contrast with the schemed proposed in [133], a third transmission mode that combines the advantages of both MIMO gains is also included. In that work, four transmit antennas are used and the hybrid mode consists in transmitting independent Alamouti schemes in each pair of transmit antennas. As a result, better system performance can be obtained due to an improved granularity in terms of symbol error rate.

2.2.6 Partners know-how and identification of knowledge gaps

In order to clearly identify partners' interests and know-how, a number of technical workshops were organized during the first year. As a result, a number of knowledge gaps were identified which, in turn, served as a starting point for the collaborative work to be conducted in ACE.

In particular, two main areas of work were identified: (1) Multi-dimensional packet scheduling and, (2) Cross-layer antenna selection strategies. For both areas of work, the pre-existing know-how along with the identified knowledge gaps are listed below.

Packet scheduling in the space, time and frequency domains for MIMO systems

R. Stridh, M. Bengtsson, and B. Ottersten, **System evaluation of optimal downlink beamforming in wireless communication**, In Proceedings of VTC Fall 2001, volume I, pages 343-347. IEEE, October 2001.

Abstract: In this paper, we investigate the use of joint optimal downlink beamforming, power control and access point allocation, in a multicell SDMA system. Smart antennas are used at the access points and single antennas are used at the terminals. The possibility to send messages to multiple terminals on the same frequency in the same time slot is exploited. An algorithm for removing users from a congested system, in order to avoid outage is proposed and evaluated Results show that the proposed algorithm gives substantial increase of the system performance compared to random removal of users.

P. Svedman, S.K. Wilsony, L.J. Cimini, Jr., and B. Ottersten, **A simplified opportunistic feedback and scheduling scheme for OFDM**, in Proc. of VTC Spring 2004

Abstract: OFDM is an attractive technique to implement multiuser diversity for the downlink. This paper deals with the problem of combining the increased cell throughput of multiuser diversity schemes with a fair distribution of resources among the users. A proportional fair scheduler for opportunistic OFDM is proposed. Its key features are that it can accommodate several quality-of-service (QoS) classes, that it has a tunable fairness level, and that it can be integrated with an opportunistic beamformer to increase system fairness. Simulation results show that the cell throughput of the opportustic scheme approaches that of a more complex smart antenna scheme for many users. For a densely populated system, the proposed scheme shows a graceful QoS degradation, possibly leading to a high average user satisfaction. The fairness parameter effectively tunes the scheduler between high cell throughput and high fairness.

P. Svedman, S. K. Wilson, and B. Ottersten, **A QoS-aware proportional fair scheduler for opportunistic OFDM**, Proceedings IEEE Vehicular Technology Conference, Fall, Sep 2004.

Abstract: Opportunistic beamforming schedules users when they experience a high instantaneous signal-to-noise ratio. Multiple antennas at the transmitter can be used to induce temporal fading to ensure that all users fade at a rate fast enough to ensure fairness. Because feedback is required, the fading rate must be fast enough to ensure fairness among the users, but slow enough so that the feedback information is not out of date. An OFDM system with opportunistic beamforming has the advantage that multiple users can be scheduled at the same time in a frequency selective channel, thus allowing a slower fading rate. However, the overhead cost of feeding back every sub-carrier for every user is very high. We propose a simplified opportunistic feedback scheme that divides the OFDM symbol into clusters. Each user feeds back a figure-of-merit listing its strongest clusters. This scheme greatly reduces the feedback overhead, without sacrificing performance significantly. In addition, the scheme has an inherent on/off waterfilling property. We compare this simplified feedback scheme in a HIPERLAN/2 scenario to a feeding back of all subcarriers and also to a smart antenna system and show that when there are many users, it outperforms the smart antenna system.

D. T. Phan Huy, V. Monteiro, A. Gameiro, J. Rodriguez, **System level performance evaluation of MATRICE air interface**, Proceedings of IST-Summit 2004

Abstract: The rapid growth of Internet services and increasing interest in portable computing devices are likely to create large demands for high-speed wireless data services in the future. Especially in the downlink, high throughput is needed since the number of downloads of large data files from web sites and servers will increase. These requirements will need to be accommodated by future Beyond 3rd Generation (B3G) cellular systems. One of the most promising candidate techniques for achieving high data rate transmission in a mobile environment is Multi- Carrier CDMA (MC-CDMA). The IST project MATRICE is dealing with research on MC-CDMA physical layer for a new cellular radio system. This new interface designed by MATRICE will provide high throughput with high mobility and will be used as a complement to current enhanced radio systems, at least during the early stages of deployment. The goal of the present paper is to present the methodology for the first throughput evaluation of MATRICE project, based on link level and system level simulations.

V. Monteiro, R. Aguiar and A. Gameiro, **Scheduling Algorithm for Beyond 3G Systems based on MC-CDMA**, WPMC 2004.

Abstract: The aim of this paper is to present a packet scheduling algorithm for an Multi Carrier CDMA based system for the broadband component of Beyond Third Generation systems, developed in the MATRICE project and intended to operate in a TDD mode at 5GHz over a 50MHz bandwidth. The priority in scheduling users is based on weighting parameters related to the application functionality and the usage of system resources. The parameters used are the Predicted Reliability in transmission, the Delay that packet is experiencing in queue and the Attempted transmissions of the packet; the Automated Repeat Request stop and wait protocol is also considered in resource management. The scheduler performance is evaluated in the downlink and the minimum set of parameter in terms of the physical channel definitions has been specified to allow the throughput evaluation by system level simulations.

D. Bartolomé, A. I. Pérez-Neira, **A Unified Fairness Framework in Multi-Antenna Multi-User Channels**, to be presented at the 11th IEEE International Conference on Electronics, Circuits and Systems (ICECS), Tel-Aviv (Israel), December 2004.

Abstract: In a multi-antenna broadcast channel, the Access Point (AP) has several alternatives for distributing the scarce resources among the users. When realistic conditions are taken into account, it is not clear which is the best suited option for the AP, since there exist a trade-off between the global performance and the individual needs. In this paper, we derive an analytical framework to study fairness in a multi-antenna multi-user channel, which is useful in practical situations. Since fairness indexes in the literature usually reflect relative performances among users, we borrow ideas from portfolio selection and propose a mean vs standard deviation analysis that allows to select a certain technique under practical conditions. We particularize this framework for a multi-antenna AP communicating simultaneously with several single-antenna terminals, and give closed-form expressions for the mean vs. standard deviation trade-off for zero forcing beamforming, dirty paper encoding, and the cooperative bound, under the assumption of a uniform power allocation among the active users. This framework can be extended to analyze other types of multi-user communications.

D. Bartolomé, A. I. Pérez-Neira, **BER-based vs. Game-theoretic Power Allocation Strategies for Multiuser MISO Systems**, in Proceedings of the X European Signal Processing Conference (EUSIPCO), Viena (Austria), September 2004.

Abstract: Motivated by the extensive use of game-theoretic strategies for uplink power control in CDMA, we compare in this paper a strategy based on the widespread utility function used in the literature with other traditional schemes based on the BER. Here, we focus on the downlink of a communication system. Basically, that utility function is a ratio between the frame success rate and the used power. It is shown in this paper that the strategy maximizing the utility implies a higher error rate than for other classical schemes, which was not shown in the literature to the best of our knowledge. Finally, we briefly discuss the usefulness of pricing mechanisms in a game-theoretic formulation of the power control.

D. Bartolomé, A. I. Pérez-Neira, **Multiuser Spatial Scheduling in the Downlink of Wireless Systems**, in Proceedings of the IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM). Sitges (Spain), July 2004.

Abstract: Optimizing a communication of a Q-antenna Access Point (AP) with K single antenna terminals is not straightforward. Since a global optimization might not be solvable in real time, the AP has several alternatives involving both the physical layer, e.g. beamforming and power/bit allocation, and the DLC, such as scheduling. The purpose of this paper is twofold. First, for $K \le Q$ we compare traditional bit allocation strategies with a novel modified approach, especially in terms of fairness. Second, we focus on the combinatorial problem that arises when $K>Q$, and propose several alternatives for the scheduling of the users into groups, which is done together with the bit allocation. Simulations show that better performance is obtained at the expense of complexity.

D. Bartolomé, A.I. Pérez-Neira, **Practical Bit Loading Schemes for Multi-Antenna Multi-User Wireless OFDM Systems**, to be presented at the Asilomar Conference on Signals, Systems, and Computers, Pacific Grove (USA) November 2004.

Abstract: This paper deals with practical multi-antenna multi-user OFDM systems. With the additional degrees of freedom of multiple antennas and multiple subcarriers, the performance might be enhanced, but the scheduling complexity might increase exponentially. Since the scheduling with realistic integer signal mappings is an NP-complete combinatorial problem, suboptimum solutions based on the scalar product are good candidates to yield a fast and realizable practical implementation. We propose afterwards a power reuse strategy to lower the computational complexity, and show that the amount of signalling can be reduced by forcing an equal mapping for all the users at the same subcarrier.

D. Bartolomé, A. I. Pérez-Neira, **Performance Analysis of Scheduling and Admission Control for Multiuser Downlink SDMA**, in Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP 2004). Montreal (Canada), May 2004.

Abstract: Multiple antennas are used here to enhance the scheduling task at a multi-antenna base station. After applying a zero forcing transmit beamforming, the scheduling shall distribute the resources among the users. Several criteria are presented and their performance in the high Signal to Noise Ratio (SNR) range is analyzed. The next issue is to take into account the SNR requirements from the users and perform the admission control accordingly. An algorithm that yields the optimum performance is proposed, together with a new criterion that falls between the optimization of the best global performance and the satisfaction of the individual needs. Simulation results are provided to show the performance of the techniques.

D. Avidor, J. Ling, C. Papadias, **Jointly Opportunistic Beamforming and Scheduling (JOBS) for Downlink Packet Access,** in Proc. IEEE International Communications Conference, Paris (France), 2004.

Abstract: Opportunistic scheduling (OS) has been proposed as a technique to improve the downlink throughput of high-speed packet systems. OS attempts to use the time varying propagation channels between the base station (BS) and the mobile stations (MSs) when they reach their peak rate capability and defer using channels when in bad state. It exploits the fact that the propagation channels between the BS and the MSs fade independently and the tolerance of many data services to delay and delay jitter. However, when the fading is slow in comparison with an acceptable packet delay, or weak, OS is not very useful. In such cases, opportunistic beamforming (OBF), a recently proposed scheme, may offer additional gains. OBF is a “natural” enhancement to OS. The enhancement amounts to replacing the BS antenna with multiple antennas and implementing an algorithm that generates a different radiation pattern every timeslot. In this paper we propose to tie the sequence of radiation patterns to the waiting times of the served MSs. We show through simulations that the scheme we propose leads to both, reduced probability of excessive packet delay and improved throughput. This can be achieved by additional processing of the feedback received from the MSs, with no additional signaling on the air interface.

A. Alexiou, et.al, Duplexing, **Resource Allocation and Inter-Cell Coordination-Design Recommendations for Next Generation Systems**, Wireless Communications and Mobile Computing magazine, Wiley, vol. 5, p.77-93, 2005.

Abstract: Coexistence of different access technologies, hierarchical cellular deployment, a wide variety of data services, requirements for transparent operation across different technologies, adaptivity to varying network conditions and mobility and Quality of Service (QoS) constraints introduce a number of challenges in the design of future generation systems and the specification of new air interfaces, such as efficiency and flexibility in the utilization of spectrum, dynamic resource allocation and exploitation of the multi-user diversity and reconfigurable interference management and inter-cell coordination. In this paper three critical issues for the design of next generation systems are addressed: i) duplexing, ii) scheduling and resource allocation and iii) interference and inter-cell coordination. A number of research directions are presented, which constitute promising potential candidates for next generation systems specification.

IDENTIFICATION OF KNOWLEDGE GAPS

Based on the partner know-how described above, the following knowledge gaps related to multi-dimensional packet scheduling were identified:

- The design of scheduling algorithms can be extended to several directions. The potential use of optimal downlink beamforming and the impact of partial or imperfect channel state information at the transmitter should be further studied. On the other hand, scheduling algorithms that take into account both physical and upper layer information deserve further attention. Techniques aimed at maximizing link layer performance (rather than physical layer performance) should be further considered. In particular, the integration of DLC issues into the scheduling modules seems very relevant in order to develop a fully integrated opportunistic system that could be implemented in future communication standards.

- Full integration of a combination of multiplexing schemes (space-time-frequency) in the scheduling algorithm and its impact on the individual/global needs of the system should be studied. For example, the combination of opportunistic schemes for systems combining OFDMA and MISO/MIMO architectures deserves further attention. MIMO scheduling techniques that are robust to imperfect CSI are still not fully developed, and need to be investigated. Also, the impact of MIMO channel modelling on the system level performance is still unclear.
- A unified framework for the design of QoS-based scheduling optimization needs to be established. Techniques that are able to balance the performance-complexity balance are particularly interesting, especially those that can be implemented in real time. Also interesting is the potential use of that type of techniques in order to balance the trade-off between global performance and individual needs in actual opportunistic systems.

Cross-layer antenna selection strategies

J. Lopez-Vicario and C. Anton-Haro**, Throughput optimisation for MIMO systems via cross-layer designs**, in Proc. 9th World Wireless Research Forum, July 2003.

Abstract: In this paper we propose a throughput maximization method for a packet switched wireless communication system with Multiple Element Antennas (MEA) based in the V-BLAST architecture. To do that, the antenna configuration is adjusted to maximise throughput instead of channel capacity and, as a result, a remarkable performance improvement is obtained. We analyze the behaviour of the system employing simple ARQ (Automatic Repeat ReQuest) protocols as Go-Back-N (GBN) and Selective Repeat (SR). Since each transmitted sub-frame over the different transmission antenna experiences different propagation channel, we propose a SR protocol working at the stream level which outperforms traditional approaches.

J. Lopez-Vicario and C. Anton-Haro, **Transmit antenna selection for rate adaptation in HSDPA systems**, in Proc. World Wireless Conference, May 2004.

Abstract: In this paper, we propose a transmit antenna selection method for a packet switched wireless communications system based in V-BLAST architecture. In order to optimize system performance, in terms of link throughput, a cross-layer design taken into account characteristics both at the physical and the link layers will be considered. Moreover, the antenna selection procedure is adapted in order to comply with the HSDPA recommendations, employing the N-SAW with Chase Combining as H-ARQ strategy. Numerical results will show this scheme features superior performance with respect to the conventional physical layer optimization method.

J. López-Vicario, C. Antón-Haro, **Joint Transmit Antenna Selection and Adaptive Modulation in Cross-Layer Oriented Designs for HSDPA Systems**, 3rd IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2004). Sitges (Spain), July 18-21 2004.

Abstract: In this paper, we propose a cross-layer design that combines antenna selection and adaptive modulation strategies in a HSDPA context. In order to optimize system performance, in terms of link throughput, both the optimal transmit antenna subset and the corresponding constellation size are jointly selected. Algorithm performance is compared with that of a scheme where transmit antenna selection and adaptive modulation processes are conducted by exclusively considering physical layer parameters. Computer simulation results show the superior performance of the cross-layer approach for which computational complexity still remains affordable.

J. López-Vicario, C.F. Mecklenbrauker, C. Antón-Haro, **Reduced-complexity Methods for Throughput Maximization in MIMO Channels**, in Proc. IEEE International Communications Conference, Paris (France), 2004.

Abstract : This paper focuses on how computational complexity associated to an algorithm for the maximisation of throughput in a Multiple-Input Multiple-Output system can be reduced. Throughput optimisation is achieved by selecting the appropriate subset of antennas on the transmit side. Given the highly non-linear nature of the throughput expression and the finite set of combinations, a straightforward approach consists in checking every single subset. However, this results in a prohibitive complexity. This paper presents two methods, named top-down and bottom-up approaches, that lower computational burden by recursively obtaining throughput expressions and, thus, avoiding unnecessary re-computations. The resulting schemes are compared in terms of number of required floating-point operations.

P. D. Karamalis, N. Skentos, A. G. Kanatas , **Selecting Array Configurations for MIMO Systems: An Evolutionary Computation Approach,** To appear in IEEE Trans. On Wireless Communications.

Abstract : This paper presents an antenna selection method for Multiple-Input Multiple-Output (MIMO) wireless systems. By exploitation of the channel transfer matrix, the antenna selection criterion is the maximization of the instantaneous capacity achieved using a specific number of transmitting and receiving antenna array elements. For each environment, the proposed method applies a Genetic Algorithm (GA) which seeks the most advantageous subset of antenna elements. The results are based on measured and simulated channels and show that the proposed method selects array configurations that yield superior performance compared to the arrays usually employed. Furthermore, comparative analysis results are presented, with respect to a state-of-the-art algorithm.

P. D. Karamalis, N. Skentos, A. G. Kanatas , **Comparison of existing MIMO antenna selection algorithms with an evolutionary approach**, COST 273, TD(04)55 Athens, Greece, 2004/January/26-27.

Abstract : In this document, a GA-based MIMO antenna selection technique, initially described in TD-03-110, is compared with existing selection algorithms proposed by Gorokhov et al. and an exhaustive search method. Comparisons are performed on both simulated i.i.d and realistic measured channels. Results show the relative advantages and disadvantages of the algorithms in terms of their capacity performance and complexity.

P. D. Karamalis, N. Skentos, A. G. Kanatas, **Adaptive Antenna Subarray Formation for MIMO Systems**, Submitted to Trans. On Wireless Communications.

Abstract: MIMO systems with reduced hardware complexity have attracted researchers' attention due to their high efficiency and low cost. Sub-optimum algorithms for antenna subset selection have been intensively studied in the literature. In this paper we present a new technique to maximize the capacity of multiple antenna wireless systems with reduced available RF chains. The technique is based on the adaptive formation of subarrays, i.e. grouping antenna elements and applying appropriate element weights. The elements of each subarray and their weights are dynamically selected by an evolutionary optimization technique using the link capacity as a cost function.

G. Pantos, N. Skentos, A. G. Kanatas, P. Constatinou, **Capacity Results from Short Range Fixed MIMO Measurements at 5.2GHz in Urban Propagation Environment**, ICC'2004, Paris, 20-24 June, 2004.

Abstract: In this paper, wideband MIMO channel measurements conducted in Athens, Greece are described. Short range scenarios with fixed transmitter and receiver, in urban like environments under LOS propagation conditions have been measured, using an 8×8 vector channel sounder operating at 5.2 GHz. Based on the measured MIMO channel matrices, results of mean and outage normalized capacity calculations are presented. These results correspond to systems with various numbers of antenna elements and various ULA antenna configurations.

N. Skentos, A. G. Kanatas, P. Constatinou, **Channel Characterization Results from Fixed Outdoor MIMO Measurements**, WPMC'2004, Padova, Italy, 12-15 September, 2004.

Abstract: In this paper, channel characterization results from fixed, short range, wideband MIMO measurements are presented. Rooftop to street scenarios have been measured, under pure LoS propagation conditions, in an urban environment at 5.2 GHz. The characterization results reported herein, refer to the delay and Doppler dispersion characteristics, coherence measures and spatial fading correlation. Also the error induced by the frequently used Kronecker product assumption is evaluated for different MIMO systems.

IDENTIFICATION OF KNOWLEDGE GAPS

The following knowledge gaps related to cross-layer antenna selection strategies have been identified:

- Current antenna selection algorithms need to be extended in order to be applicable to multi-user scenarios. In this scenario, the possibility of combining cross-layer scheduling techniques together with antenna selection methods could be further explored.
- Antenna-selection techniques that are able to switch between multiplexing and diversity gain based on cross-layer information (i.e., in order to maximize the performance of higher layers) need to be considered.

A complete comparison and benchmarking of current antenna selection procedures based on cross-layer information is needed. New antenna selection methods based on evolutionary programming techniques could be further explored.

2.2.7 Outcome of Joint Research and Future Actions

The main outcome of the joint research performed during the first phase of ACE in the framework of the Cross Layer Smart Antenna Systems Optimisation Networks can be summarised as follows:

- Evaluation and compilation of the state of the art in the area of cross-layer design for smart antenna systems and multi-antenna scheduling techniques;
- Identification of the functional and architectural requirements for cross-layer optimization in multi-antenna systems and evaluation of the impact of multi-antenna architectures in opportunistic schemes;
- Identification of the open issues, challenges and knowledge gaps related to these fields and selection of relevant problems according to their potential impact in current and future communication standards;
- Definition of a common approach to address the selected issues/challenges, targeting both multi-antenna opportunistic communications and cross-layer antenna selection strategies;
- The above common approach has been implemented and evaluated in the framework of several activities the ACE partners are currently participating (e.g. other research projects) and the results produced therein have been disseminated internally and analysed within ACE.

In the context of ACE2, the partners plan to continue the above-described activities. The application of multi-antenna systems in opportunistic communications and the potential gains that can be obtained from the cross-layer paradigm, are relevant problems that will certainly play a major role in the definition of future communication systems. In ACE2, the impact of these multi-antenna architectures will be further explored and demonstrated.

3 Integration Activities

Integration among the partners of ACE working in the area of Smart Antenna System Level Strategies and Cross Layer Optimisation has been achieved in various aspects:

- Exchange of views on the state of the art
- Sharing of expertise on specific research items
- Assessment of the state of the art and identification of knowledge gaps along with an approach to address them based on partners individual expertise
- Sharing of simulation data
- Planning to perform simulations with the use of a common platform
- Examples of the impact on teaching, and Master/PhD research agenda are given analytically in Section 4.1.
- Examples of integration of joint research through joint papers are given in sections 3.1-3.3.
- The members of the Scientific Council played an important role in the integration carried out within ACE, as explained in Section 3.4.

3.1 Elaboration of a joint conference paper (CTTC, KTH)

This publication is a direct result of the collaborative work conducted by the KTH and the CTTC in the context of ACE. In particular, the problem of transmit beamforming, power allocation, bit loading, and admission control in a multi-user scenario has been addressed, where several single antenna mobile terminals are served by one base station equipped with an antenna array. Furthermore, the impact of using either optimal or zero-forcing transmit beamforming schemes in combination with different bit allocation strategies was investigated, namely the Maximization of the Sum Rate (MSR), the Maximization of the Minimum Rate (MMR) and a modified version of the latter, for a finite set of modulation schemes. The performance evaluation was conducted by means of system-level simulations, using a realistic channel model for urban micro cells, with an emphasis not only on the aggregated cell throughput but also on the associated fairness issues. The bibliographic reference is as follows:

M. Bengtsson, D. Bartolomé, J. L. Vicario, C. Antón-Haro, "Beamforming and Bit-loading Strategies for Multi-User SDMA with Admission Control", PIMRC 2005. Berlin (Germany), Sept. 2005.

- *Participants*: CTTC and KTH.
- *Dates and duration:* Collaborative work was conducted in the period Dec'04-Mar'05. The paper was presented in Sept'05 during the PIMRC conference.
- *Outcome and future actions:* This joint paper is available for downloading from http://www.cttc.es/publications/international/2005.htm and http://www.antennasVCE.org.

3.2 Elaboration of a joint conference paper (LUCENT, IT)

This publication is a direct result of the collaborative work conducted by IT and LUCENT in the context of ACE. In particular the problem of QoS based multi-user scheduling in MIMO systems has been addressed. Packet scheduling techniques exploiting multiuser diversity have been proposed in order to improve the throughput of high-speed packet systems. However, the use of techniques that take the scheduling decisions based only on the channel conditions, may fail to provide the desired QoS, as the maximum allowable delay is an important parameter, and therefore algorithms aiming at providing QoS should combine QoS related parameters with the channel conditions. In this paper we consider two algorithms that address this issue. One algorithm has been developed to improve the opportunistic beamforming technique by tying the sequence of radiation patterns with the waiting times of the served mobiles, while the other weights the waiting times and channel reliability to schedule the packets while using beamforming to spatially reuse the radio resources in a CDMA scheme. We show through simulations that such schemes lead to reduced probability of excess delay while keeping a high throughput.

A. Gameiro, J. Reis, A. Alexiou, "QoS-based multiuser scheduling in MIMO systems", 16th Annual IEEE International Symposium on Personal Indoor and Mobile Radio Communications, Berlin, Germany, September 2005.

- *Participants*: LUCENT and IT.
- *Dates and duration:* Collaborative work was conducted in the period Dec'04-Mar'05. The paper was presented in Sept'05 during the PIMRC conference.

3.3 Elaboration of a Journal Paper (CTTC, KTH, LUCENT and IT)

This paper is aimed at providing an introduction and an overview of the state of the art concerning cross-layer scheduling for wireless MIMO systems. The paper addresses the following topics: capacity in multi-user MIMO systems, channel-aware scheduling, channel- and queue-aware scheduling, opportunistic beamforming, selective multi-user diversity, spatial vs. multi-user diversity trade-offs, space-frequency scheduling. At the time of this writing, the paper is in production and will be submitted before the end of Dec'05.

- *Participants:* CTTC, LUCENT, KTH, IT.
- *Dates and duration:* Dec'05 (submission)
- *Outcome and future actions:* This paper will serve as a tool for the dissemination of the research topics addressed within workpackage WP2.2-4 in ACE.

3.4 Interaction with the members of the Scientific Council

The involvement of the Members of the Scientific Council, especially the ones specialising in Signal Processing and Smart Antennas (Prof A. Paulraj and Dr J. Winters), in the integration of ACE has been instrumental in:

- Supervising the research directions
- Observing the dissemination activities
- Participating in the ACE Special Session at PIMRC 2005 and interacting with the ACE researchers

- Giving keynote presentation at the PIMRC Plenary sponsored by ACE:
    - “Smart Antenna Techniques and Application to Ad Hoc Networks” by Dr. J. Winters, Motia Inc.
    - “OFDMA, MIMO, OS and IM– Key Ingredients for Mobile Broadband”) by Prof. A Paulraj
- Most importantly, giving advice on future research directions, which are valuable for the organisation of the research activities in ACE 2. Their suggestions include the following topics:
    - MIMO for IEEE 802.16e and 802.11n standards
    - Cooperative MIMO and SDMA concepts
    - Low complexity MIMO receivers design

4 Spreading the Excellence and Education Activities

In the previous section, a number of actions aimed at facilitating the integration of research efforts *among* the partners in ACE were presented. Going one step beyond, activities listed below have been undertaken in order to make either the scientific community or broader audiences within ACE aware of the R&D progress resulting from NoE evolution. In spreading excellence, PhD/Masters theses projects, the European School of Antennas (EuSA), scientific journals, workshops and conferences turn out to be very valuable tools.

4.1 PhD/Masters These Projects

4.1.1 PhD Thesis Project on Utility Based Scheduling Algorithms for MIMO Systems

The aim of this thesis is to develop cross-layer based scheduling algorithms for packet switched wireless systems employing multiple transmitting and receiving antennas. The cross-layer approach is dictated by the requirement that future generation telecommunication networks will have to provide QoS, and then scheduling algorithms should take into account the physical environment characteristics with the individual requirements of the traffic. The approach to be followed will be based on the concept of utility, where the aim is to maximize the overall utility to the network. The issues currently faced are: the definition of meaningful utility functions, selection of a relevant reduced set of parameters for MIMO systems. The PhD thesis will be in part supported by the ACE network and is expected to align its objectives according to the research issues identified in the NoE.
The project started in September 2005 at IT.

4.1.2 Joint PhD program at IT with University of Porto

In the framework of preparation of a joint PhD programme between Univ. of Aveiro and Univ of Porto in Telecommunications, a brief presentation was made by IT concerning the activities of ACE, in order to point out the research issues that are currently considered relevant in the filed of antennas. This is to be considered as an input for the definition of the PhD programme, which is currently under preparation.

4.1.3 Masters Thesis Project on Cross-layer Techniques for Optimisation of Wireless Systems

This thesis explores cross layer design for resource allocation in MAC layer for wireless packet switched data networks, such as cellular networks. The main objective is to improve the system performance by incorporating the information from the physical layer and the network layer into the design of resource management. To achieve that goal, we first address the evolution of mobile communications, from its first generation, 1G, to the latest 3G and give a glimpse of foreseeable future of 4G networks. Then we address the issue of cross layer networking and we will outline the basic principles and challenges of cross layer design in wireless networks, and we will discuss the tradeoffs involved.

A wireless communication system is presented and investigated which is based on a joint design of layers and a comprehensive information exchange between them. We present an algorithm intended for usage in the process of packet scheduling transmission between a base station and mobile terminals. The objective is to jointly exploit the temporal variation in users channel conditions to opportunistically select users with best potential, while also ensuring that resource allocation fairness and Quality of service (QoS) constraints are satisfied.

The results shows that within the OSI layered architecture, it is possible to yield significant gains, if the system optimizes the performance by making use of the interaction across protocol layers.

The project started in September 2004 and finished in June 2005. A Masters thesis dissertation was produced:

> J. Reis, Cross-layer techniques for optimisation of wireless systems, Univ. of Aveiro, June 2005 (in Portuguese)

Part of the work was carried out under the scope of the ACE project and presented in [135] and [136].

4.1.4 Masters Thesis Project on Dynamic Resource Allocation Algorithms for MC-CDMA based 4G systems

This work in this project proposes a packet scheduling algorithm for MC-CDMA based system for the broadband component of the Fourth Generation mobile systems. The algorithm combines services requirements and link quality information to prioritize the packets. The performance of proposed algorithm is compared in terms of user satisfaction with the algorithm that maximizes the cell throughput.

This work includes the evolution of the mobile communications systems towards what is supposed to be the 4th generation, by the standardization and scientific community. It is also described the studies carried on by the IST MATRICE project, whom this work was developed for, including the support access technologies.

Since system level studies are performed widely with recourse to simulations, is presented the system level simulation model used to simulate the MC-CDMA based system. The system level simulation model includes simplified interfaces models to the physical layer and to the IP layer, to avoid complex and heavy simulations. Physical layer interface included average value interface to be used in simulations of real-time applications, where session duration is longer than coherence time of the fading radio channel. Actual value interface is used for packet based applications where the session duration is short when compared to the coherence time of the fading radio channel.

The evaluation of the proposed scheduling algorithm is performed using a resource management system based on the 3GPP HSDPA which includes adaptive modulation and coding, Hybrid ARQ with Chase combining.

The results showed that when compared to maximum throughput algorithm, the proposed algorithm is the most suitable for packet scheduling when services requirements and user satisfaction should be tacked into account. More over the results the performance is a trade-off between the number of satisfied user and the cell throughput. Appropriate parameterization allows adjusting the proposed algorithm to different behaviours according to the type and load of the traffic in the system.

The project started in September 2004 and finished in June 2005. A Masters thesis dissertation was produced:

> V. Monteiro, Dynamic resource allocation algorithms for MC-CDMA based 4G systems, Univ. of Aveiro, June 2005 (in Portuguese)

Part of the work was carried out under the scope of the ACE project and presented in [137]and [138].

4.2 Lecture at a course within the framework of the European School of Antennas –EuSA

CTTC actively collaborated in the course "MIMO Communication systems and antennas" by giving a lecture entitled "Capacity and scheduling in multi-user MIMO systems- A cross-layer approach" (by Dr. C. Anton-Haro). The course dealt with MIMO communication systems in terms of signal processing and resource allocation and antennas for such systems, in particular small antennas for MIMO terminals. The course featured lectures as well as computer exercises and real-world hands-on laboratories, structured into three parts: computer based antenna-design and evaluation, signal processing laboratory on a real MIMO test-bed and talks on signal-processing, and resource allocation in multi-user MIMO systems. In addition, one engineer from CTTC attended the course as a student.

- *Participants:* Telecommunications Technological Center of Catalonia (CTTC). The course was organized by the KTH and the Helsinki University of Technology.
- *Dates and duration*: Stockholm, Sept. 5-9
- *Outcome and future actions:* More information, including course contents and slidesets can be found at http://www.antennasvce.org/Education/ESoA/view?folder=9. As a result, both CTTC and KTH are organizing a new course on Cooperative Communications for the European School of Antennas (ESoA) to be taught in Q4/2006.

4.3 Lectures at the ACE-NEWCOM workshop during the IST Mobile Summit

The ACE-NEWCOM workshop was held on June 23, 2005 in Dresden (Germany). More information and slidesets available at http://mobilesummit2005.org/session.php?session=102

4.3.1 Lecture on Flexible MIMO Architectures

CTTC actively collaborated in the workshop on "Smart Antennas, MIMO and Multiuser Systems" by giving a lecture entitled "Flexible MIMO Architectures: Guidelines in the Design of MIMO Parameters" (by Prof. M. A. Lagunas). The objective of this workshop was to present the highlights of the work performed in the framework of ACE and NEWCOM and discuss the most recent developments and promising future directions in the field. According to the organizers of the IST Summit, this workshop was the most subscribed one, this reflecting its impact in terms of dissemination and visibility.

4.3.2 Lecture on Scheduling, Diversity and QoS Issues

This presentation was given by IT during the joint ACE-NEWCOM workshop in Dresden at the IST Summit 2005. The presentation focused on the relations between multiuser diversity, scheduling and QOS issues. The motivation for the work described was the current trend observed in telecommunication networks, regarding the need to provide QoS which means differentiated treatment for different users / traffic / applications. As the scheduler is one of the major components for the provision of QoS, its design has to done taking into account the service / application requirements. On the other hand due to the dynamic nature of the network topology and channels in wireless systems, it cannot ignore either the PHY layer information, therefore calling for a cross-layer design. The presentation discussed the various options to combine QoS requirements and PHY layer information, and introduced a design methodology based on the concept of global utility.

4.4 Organization of a Plenary Session at PIMRC'05

CTTC participated in the organization of the Plenary Session on Physical Layer aspects at PIMRC'05. In particular, two out of the three talks were given by ACE experts Dr. J. Winters, Motia Inc ("Smart Antenna Techniques and Application to Ad Hoc Networks") and Prof. A Paulraj ("OFDMA, MIMO, OS and IM– Key Ingredients for Mobile Broadband"). Both talks were sponsored by ACE and this extent was conveniently publicized in the event.

- *Organizer:* CTTC.
- *Dates and duration:* Sept 12, 2005.
- *Outcome and future actions:* This visit gave ACE researchers attending the conference the opportunity to meet face to face with ACE experts to discuss both the current status and future evolution of collaborative R&D within ACE-2. Slidesets and audio recordings are available for download from http://www.antennasVCE.org

4.5 Joint editorship of Special Issue at EURASIP's Signal Processing Journal

A special issue of EURASIP's Signal Processing Journal on "Advances in Signal Processing-assisted Cross-layer Designs" will be published in Q4 2005. This Special Issue attempts to provide an overview of the research activity in this field, with emphasis in how such cross-layer designs can benefit from recent advances in signal processing. In a wireless context, most of the work focuses on strategies aimed at matching the instantaneous radio channel conditions with mechanisms for reliable transmission and, also, traffic and congestion conditions. In doing so, cross-layer signalling is regarded as a key enabler and, hence, several methods are emerging to embed such signalling in current layered protocol stacks. By facilitating inter-layer cooperation or, further, by co-designing functionalities residing at different layers in the protocol stack, one can optimise the always scarce radio resources, namely, bandwidth and transmit power. Such cooperation, though, should be cautious since cross-layer designs might result in unintended and adverse interactions with other OSI layers. Hence, there exists a fundamental trade-off between system performance and stable architectural design. More information: http://www.cttc.es/spjournal

- *Participants:* CTTC and UPC, editors.
- *Dates and duration:* To appear in Q4/2005.
- *Outcome and future actions:* Table of contents to be made available soon at http://www.eurasip.org/content/default.asp?page=s9_1

4.6 Workshop Organisation

4.6.1 ACE workshop at the IST Summit

A workshop has been **organised in the framework of the IST Mobile Summit 2005**, jointly with the NEWCOM Network of Excellence, on **June 23, 2005**. The theme of the workshop was "**Smart Antennas, MIMO and Multiuser Systems**" and consisted of the following invited presentations:

- Prof. Miguel Ángel Lagunas (CTTC, Spain): Flexible MIMO Architectures: Guidelines in the Design of MIMO Parameters
- Prof. Shlomo Shamai (Technion, Israel): MIMO broadcast channel capacity
- Pr. Robert Fischer (University of Erlangen, Germany): Precoding techniques for the MIMO broadcast channel
- Prof. David Gesbert (Eurecom, France): Scheduling and multiple antennas, a cross-layer design
- Prof. Raymond Knopp (Eurecom, France): Multiuser diversity and fairness in delay-limited wireless cellular networks
- Dr. Panagiotis Karamalis (ICCS/NTUA, Greece): Reduced Hardware Complexity MIMO Systems with Enhanced Capacity Performance
- Prof. Atilio Gameiro (IT, Portugal): Scheduling and multiuser diversity
- Prof. Panagiotis Demestichas (UPRC, Greece): Design of context-aware, reconfigurable, high-speed wireless access systems

All of the partners of WP2.2-3 and WP2.2-4 participated in the workshop and contributed in the work presented.

The workshop attracted a great amount of attention both within the ACE and the IST community and the international research community, with attendees from Europe, Asia and America. It was the most attended workshop of the IST Summit with over 40 registrations. It offered the opportunity to ACE partners to gain exposure for their work and exchange views with researchers in the field.

The workshop generated very interesting technical discussions and exchange of views and initiated follow-up discussions and further interactions with organisations outside ACE from Europe, Asia and America. The workshop received many positive comments from the IST and the international research community and numerous requests for access to the material of the presentations.

More details and the presentation files can be found on the workshop's website (**`http://mobilesummit2005.org/session.php?session=102`**).

Due to the great success of the ACE workshop at the IST Summit –and with the encouragement of EC - the plan is to continue (in ACE2 and beyond) and try to establish the organisation of a Smart Antenna workshop in the framework of the IST Summit.

4.6.2 ACE special session at PIMRC

A special session on " Cross-layer MIMO Designs" was organized during the last Personal Indoor Mobile and Radio Communications Conference in Berlin (PIMRC, Sept'05). The special session featured contributions by partners involved in ACE reflecting results from on-going joint research activities, as well as selected contributions by partners in NEWCOM as well as third parties. The event was organized by the CTTC and the following papers were presented:

- Fair scheduling and orthogonal linear precoding/decoding in broadcast MIMO systems. *Politécnico di Milano.*
- QoS-based multiuser scheduling in MIMO systems. *Instituto Telecomunicaçoes* and *Lucent*.
- Beamforming and bit-loading strategies for multi-user SDMA with admission control. *KTH and CTTC.*
- Cross-layer optimization for a multi-user MIMO audio transmission. *Ilmenau University of Technology.*
- Resource allocation in wideband wireless systems. *CTTC, Institut Eurecom* and *UPC.*

Finally, it is worth noting that participants in this session have engaged in further interactions and joint research activities and some additional joint papers are in production.

5 Conclusions

The main outcome of the joint research, integration and dissemination performed during the first phase of ACE in the framework of System Level Strategies for Smart Antenna Networks and the Cross Layer Smart Antenna Systems Optimisation can be summarised as follows:

- Assessment of the state of the art in the area of system level methodology;
- Identification of the requirements and critical parameters particular to the case of multiple antenna networks;
- Definition of a common approach to address the open issues/challenges associated with a system level methodology suitable for next generation broadband, multi-antenna networks;
- Evaluation and compilation of the state of the art in the area of cross-layer design for smart antenna systems and multi-antenna scheduling techniques;
- Identification of the functional and architectural requirements for cross-layer optimization in multi-antenna systems and evaluation of the impact of multi-antenna architectures in opportunistic schemes;
- Definition of a common approach to address the selected issues/challenges, targeting both multi-antenna opportunistic communications and cross-layer antenna selection strategies;
- Impact on teaching, and Master/PhD research agenda;
- Organisation of short courses;
- Publication of joint conference papers, contributions to IST, WWRF and preparation of journal paper;
- Organisation of the ACE workshop on “Smart Antennas, MIMO and Multiuser Systems” at the IST Summit 2005, and
- Organisation of the ACE special session on " Cross-layer MIMO Designs" at IEEE PIRMC 2005.

In the context of ACE2, the partners plan to continue the above-described activities, in an effort to further refine the identified common approaches and optimise their applicability in terms of striking the right balance between computational complexity and accuracy for different sets of assumptions and scenarios. The application of multi-antenna systems in opportunistic communications will be further explored along with the potential gains that can be obtained from the cross-layer paradigm.

Within the framework of ACE2 and building upon the achievements of ACE, the partners plan to enhance the education and dissemination activities also leveraging on the valuable guidance of the members of the Scientific Council.

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7 Terminology

AMC	Adaptive Modulation and Coding
AoA	Angle of Arrival
AP	Access Point
API	Application Program Interface
BER	Bit Error Rate
CL	Cross Layer
CSI	Channel State Information
CSIT	Transmitter Channel State Information
CSIR	Receiver Channel State Information
DLC	Data Link Control
HARQ	Hybrid Automatic Repeat Request
LoS	Line of Sight
MAC	Medium Access Control
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
MS	Mobile Station
OFDM	Orthogonal Frequency Division Multiplexing
PHY	Physical layer
QoS	Quality of Service
SDMA	Space Division Multiple Access
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SNIR	Signal to Noise and Interference Ratio
SNR	Signal to Noise Ratio
SVD	Singular Value Decomposition
TDMA	Time Division Multiple Access
ZF	Zero Forcing