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### First Report of the Activities on Feedback and Resolution of the Channel State

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#### **Abstract:**

This deliverable presents an overview of the activities pertaining to feedback and imperfect channel estimation and the interplay between the two in the form that is considered in NEWCOM<sup>++</sup> WPR.2. We provide a description of the integration activities with other WPR from the network in addition to an up-to-date description of the three tasks of WPR.2 namely, Imperfect channel estimation (TR2.1), Point-to-point and Point-to-multipoint, Two-Way Channels (TR2.2), and Precoding Techniques for the MIMO Broadcast Channels (TR2.3). Cross-WPR and Cross-project integration efforts through platform activities are also described.

**Keyword list:** Channel Estimation, Unknown Channels, Feedback, MIMO Broadcast channels

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## 1 INTRODUCTION

WPR.2 aims to explore two crucial aspects in broadband wireless communications, namely the resolution of the channel state at the receiver and the use of feedback. These are related primarily since feedback of channel state information is becoming an integral part of modern wireless networks, both from the point-of-view of resource scheduling and advanced multi-antenna signal processing and therefore the ability to resolve the channel at the transmitter is ultimately related to what can be estimated at the receiver.

This document presents the work carried out in 2009 in the context of WPR2 with a primary focus on the joint research activities covering at least two partners from the network. Integration with other activities in Newcom<sup>++</sup> are provided in Section 2 along with a high-level description of WPR.2 tasks. Sections 3,4 and 5 respectively detail the activities carried out in 2009 in each of the three tasks as well as those which are planned in 2010-2011, in particular with respect to interaction with new FP7 projects (SAMURAI, LOLA) whose application areas are strongly related to the scientific output of WPR2. Section 6 presents some conclusions.

### 1.1 Glossary

SNR	Signal to noise-ratio
DMT	Diversity-Multiplexing Tradeoff
FDD	Frequency-Division Duplex
TDD	Time-Division Duplex
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple-Access
LTE	Long-term Evolution of UMTS
UMTS	Universal Mobile Telephony System
CSI	Channel State Information
CSIT	Transmitter-end Channel State Information
CSIR	Receiver-end Channel State Information
MIMO	Multiple-Input Multiple-Output
MU-MIMO	Multiuser Multiple-Input Multiple-Output
BC	Broadcast Channel
MAC	Multiple-Access Channel
SISO	Single-Input Single-Output
BER	Bit Error-Rate
ZF	Zero-Forcing
MMSE	Minimum Mean-Squared Error
DFE	Decision Feedback Equalizer
DOF	Degrees of Freedom
BS	Basestation
MS	Mobile Station
OSTBC	Orthogonal Space-Time Block Code
LR	Likelihood Ratio
ML	Maximum-likelihood
ST	Space-time
MSE	Mean-squared Error
COSTBC	Complex Orthogonal Space-Time Block Code
MRC	Maximal Ratio Combining/Combiner

## **2 OVERVIEW OF WPR2 TASKS AND RESULTING JOINT ACTIVITIES**

### **2.1 TR2.1 Overview**

TR2.1 considers the effects of the ability or not of a transmitter or receiver to resolve the channel state. Channel estimation is the process by which the receiver resolves the channel state. It is well-known that as systems become more and more rich in terms of bandwidth and spatial processing (transmit antennas), which is what we are witnessing in the evolution of 3G networks and will surely continue in the future, the number of degrees of freedom to be estimated increases. This increase is approximately linear in both bandwidth and spatial dimensions for practical channel bandwidths. Moreover, due to the mobility of user terminals and objects in their vicinity the channel does not remain constant for long periods of time (a few milliseconds suffice for the channel to have changed completely). This is particularly true in cellular networks where support for high-mobility is an ever-increasing feature. As a result of both these facts, resolution of all degrees of freedom characterizing the channel state is a difficult task.

Although it is well understood that channels are time-varying, a proper analysis of the resulting effects on system performance even for one-way communications is still incomplete. Significant headway has nonetheless been made in very recent years, both from the point-of-view of information-theoretic limits and error-rate characterization. More analytical work is required for broadband MIMO channels to put to rest the analytical treatment of channel state resolution. Furthermore, more refined practical techniques inspired from this analysis combining channel estimation and decoding are still active areas in the wireless communications research community.

Joint work by EURECOM and UCL/Gent was initiated in 2009, although no publications have resulted from this collaboration at present.

Joint work was continued by EURECOM and FTW in the area of universal space-time code design on arbitrary channels and resulted in one journal submission of extremely high-quality and several conference publications.

### **2.2 TR2.2 Overview**

A key feature of most modern radio systems is the fact that they allow for two-way communication. This allows for a sharing of the medium in both directions for both communication and low-layer signalling of channel quality indicators and decoding capacity indicators. This is the primary subject of TR2.2. In addition to studying the effect of imperfect channel knowledge at the receiving end we strive to study methods to encode it for the return channel as a function of the allocated bandwidth for feedback. Proper exploitation of incomplete feedback for both point-to-point two-way channels and multiuser/broadcast channels is still a very open area for research.

One set of joint activities within TR2.2 were carried out by EURECOM, CTTC and UPC and have already lead to joint publications. Joint Work was initiated between EURECOM and FTW in the area of feedback strategies for reciprocal two-way channels. The latter is planned to be tested in 2010-2011 on the OpenAirInterface.org platform in the context of extensions to LTE signalling to take advantage of channel reciprocity in TDD deployments.

### **2.3 TR2.3 Overview**

TR2.3 covers what is most likely the key practical problem in wireless communications today, namely precoding for the multi-antenna broadcast channel. This is a model for the downlink in a cellular network, where multiple-antennas (at least 4) are used in current 3GPP standards (LTE, LTE-A) combined with feedback channels for channel state information and decoding capacity indicators. Based on existing theoretical research, which focuses on multi-antenna wireless broadcast channels, it is well understood now, that precoding is fundamental in the strive to design modern wireless

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communications systems that will approach theoretical bounds. This subject attracts recently massive attention of researchers, and has also emerged in future wireless standards. While serious theoretical progress has been reported as of late, addressing a variety of state of art concepts, such as dirty-paper coding. Yet the understanding of efficient robust approaches which cope with practical conditions is in its preliminary stages. One of the central aspects that calls for a deeper understanding is the impact of the accuracy of channel state information (CSI) on various communications strategies. Under ideal assumptions, recent theoretical developments do identify the optimal approaches. Once we deviate from ideal assumptions, it is unclear what constitutes the optimal strategy. Even within the restricted class of linear precoding techniques, such as zero-forcing, there is no clear understanding how to operate under these practical assumptions, and exhibiting robust features. The study focuses on precisely these aspects, which we believe have both theoretical and practical implications. The goal will focus on gaining analytical understanding of the optimal linear approaches under different models which reflect partial knowledge of the CSI parameters

We consider further non linear robust precoding strategies relying on information theoretic insights and aimed at identifying robust techniques within the class of dirty-paper approaches, as well as more practical general vector perturbation methods. Finally, the precoding techniques are intimately linked with proper scheduling and required feedback information about CSI, which essentially touches also upon network aspects. Scheduling and CSI feedback demands cannot be interpreted as a stand-alone entities, but rather as an inherent part of a unifying approach of robust precoding. We plan on conducting research to the end of understanding the basic role of the quality of CSI needed at transmitting ends, as to provide the full promise of precoding, and primarily the superior multiplexing gain. This effort will include also an attempt to identify ultimate theoretical bounds on minimal demands of the feedback link that maintain optimal performance, in terms of multiplexing gain (degrees of freedom) as well as the gap to capacity. Comparison to actual robust pre-processing schemes is also planned, and is to be compared to the ultimate bounds.

Joint work was performed by CTTC and UPC in this task resulting in several publications reported in Section 4. Joint work of a fundamental nature between SUPELEC and Technion was initiated, and has resulted in resulted in publications in 2009 in addition to new submissions for 2010.

## **2.4 WPR2 in Newcom<sup>++</sup>**

The relationships between WPR2 and other of Newcom<sup>++</sup> activities are shown in Figure 1. These 2009-updated relationships are detailed in section 2.4.1.

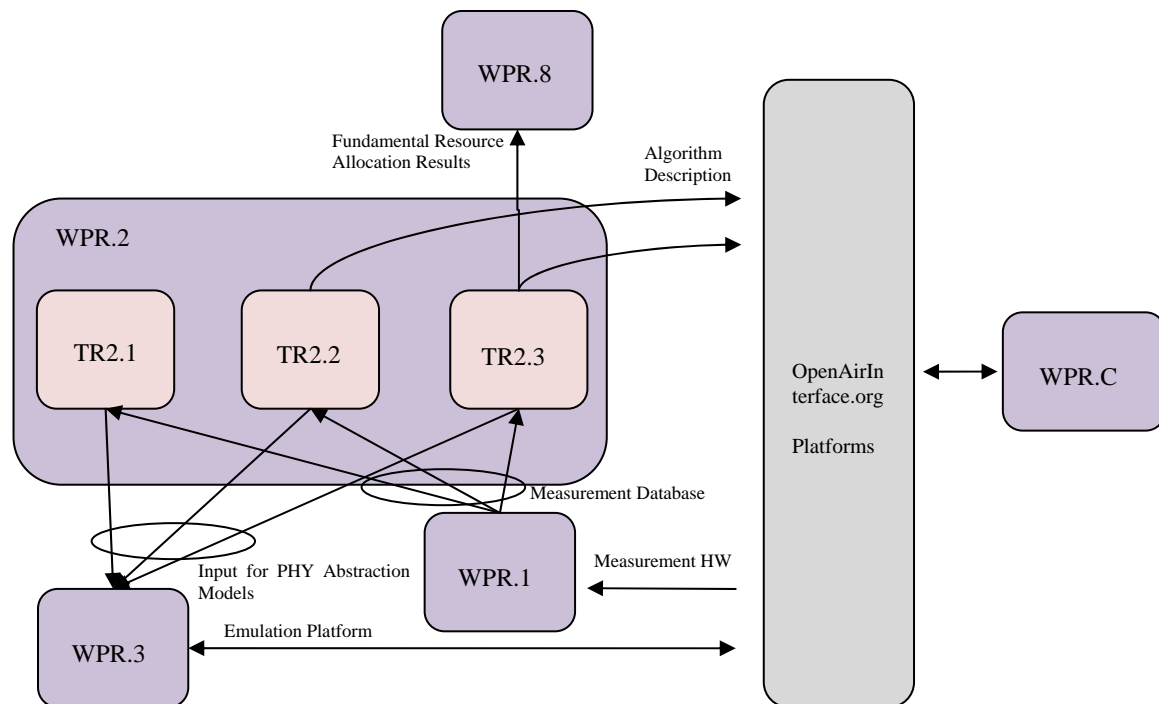


Figure 1: WPR.2 in Newcom<sup>++</sup>

#### 2.4.1 Interactions with other WPR

Here we provide a simple summary of the foreseen and ongoing interactions of WPR.2 with other WPR.

##### WPR.1

The subject of WPR.1 is wireless channel modeling and measurement. Channel models are fundamental to accurate analysis of system performance and fundamental communication limits, whether the metric is link or system information rate or link error probability. As a result, there is a very strong relationship between WPR.1 and this workpackage, in the sense that channel modeling aspects will be used as input to analysis. Concrete interaction has begun with WPR.1 activities in the sense that the measurement and modelling activity related to MU-MIMO channels has been used for joint-work in WPR.2 on empirical system performance analysis and feedback signalling design. This activity will surely continue. An explicit inter-WPR activity related to exploitation of reciprocity based on two-way auto-calibration in TDD systems began in 2009 (CNRS-EURECOM/FTW).

##### WPR.3

WPR.3 considers adaptive modulation and coding schemes and abstraction models for physical-layer processing. This work firstly relies heavily on both feedback schemes based on channel quality indicators in order to adapt coded-modulation strategies dynamically. Here WPR.2 can provide input regarding feedback protocols for next-generation wireless coding systems, primarily Hybrid-ARQ-based adaptive modulation and power-control strategies. In addition, information regarding the dimensioning of feedback channels and the granularity of the information used for feedback will be provided. The second important aspect of WPR.3 which can make use of the results of WPR.2 is physical-layer abstraction techniques. The latter requires accurate models for system performance, for instance error-rates of link. Here, WPR.2 should provide accurate characterizations of coded MIMO-OFDM channels under imperfect knowledge of channels at both ends of the communication link.

Concrete interaction (in the context of WPR.3) has begun in the context of PHY abstraction models and integration with the OpenAirInterface.org ([www.openairinterface.org](http://www.openairinterface.org)) emulation platform in 2009

(CNRS-EURECOM/NKUA). Transceiver mechanisms developed in WPR.2 will be modelled for simulation purposes in WPR.3.

### **WPR.8**

WPR.8 considers scheduling and adaptive radio resource assignment and can make use of the work here in a similar sense to WPR.3. The main difference is that system-wide (multi-user) results are pertinent as opposed to point-to-point link characterizations. This applies primarily to the WPR.2 work on MIMO broadcast techniques for single and multi-cell cellular systems.

As was the case in 2008, no concrete interaction has begun.

### **WPR.C**

WPR.C is dedicated to hardware platforms and real-time algorithm implementation. It was decided in 2008 that the third generation OpenAirInterface.org hardware platform will be one of the common platforms of WPR.C. As a result, algorithmic work carried out in WPR.2 could be ported to this platform since CNRS-EURECOM is the main developer of algorithms for this target. The joint-work of CNRS-EURECOM/CTTC/UPC in the context of feedback signalling mechanisms and practical channel estimation strategies is a target for this type of activity. In addition, the two-way firefly synchronization and distributed MIMO transmission have already been ported to the second generation OpenAirInterface.org platform. The latter were demonstrated at the ICT mobile summit and N++ dissemination event (see Section 2.5)

EURECOM and RWTH (both members of WPR.2 and WPR.C) have initiated a joint-activity in the context of WPR.C on baseband processing architectures using the OpenAirInterface.org baseband platform and RWTH ASIP design methodologies. This was launched at the end of 2009 and will continue throughout 2010. The output of this will be a inner-MODEM processing engine for advanced MIMO receivers (channel estimation, data detection) and can be used to demonstrate WPR.2 algorithms from TR2.1. It is unclear whether the target platform will be ready in time for such algorithmic integration within the time-frame of the NoE. Nevertheless, the architecture has been designed with such algorithms in mind and EURECOM is committed to full algorithmic integration on the baseband engine. This work establishes a very clear link between WPR.2 and WPR.C.

## **2.5 WPR2 Integration with Platforms**

In 2008-2009 it was decided to include a small platform activity in WPR.2 in order to foster inter-WPR collaboration and for dissemination purposes on a selected set of scenarios. The important benefit of this activity was felt during the dissemination day in March 2009, where some of aspects of these platform activities were demonstrated. In the context of WPR2 it is used to analyze two-way MU-MIMO signaling strategies and their resulting system performance (EURE/CTTC/UPC and EURE/FTW in 2009-2010). This is carried out not on simulated or modelled channels, but on real mobile MIMO channel traces. In addition, real-time two-way distributed network synchronization and distributed MIMO processing (3 nodes) algorithms were also integrated onto the platform.

The WPR.2 use of the OpenAirInterface.org platform was demonstrated both at the dissemination day and at the ICT Mobile Summit at the N++ booth.

## **2.6 WPR2 Integration with New FP7 Call 4 Projects**

The scientific output of WPR2 will also be injected, to a certain extent, into two new FP7 Call 4 projects which have overlapping areas of interest:

- Achieving Low-Latency in Wireless Communications (LOLA)
- Spectrum Aggregation and Multiuser-MIMO Real World Impact (SAMURAI)

Both projects are partially focused on physical layer processes applicable to advanced LTE/LTE-A technologies. EURECOM is a key partner in both these projects and will bring its applicable N<sup>++</sup> developments to these new projects as of 2010 in the form of more concrete realizations than those possible in N<sup>++</sup>. In addition, the ideas will be mostly related to feedback signalling mechanisms for low-latency transmission and MU-MIMO transmission strategies. In addition, the industrial partners in these projects will have access to the new developments (primarily Thales, Ericsson, Nokia, Siemens). The relationship with N<sup>++</sup> was clearly identified during the preparation of these projects.

### **3 TR2.1 ONGOING ACTIVITIES IN 2009-2010**

#### **3.1 Fundamental Limits of Non-Coherent MIMO Communications (CNRS-EURECOM)**

The work of Salim and Slock in 2008 on non-coherent was extended to more general (multiuser) unknown channel models in [43][44]. In [43] a system comprising of a multiple antenna enabled base station (BS) and multiple single antenna users is considered. In such cases, very high data rates can be obtained if BS transmits to multiple users simultaneously. This simultaneous transmission to multiple users over the same bandwidth is realizable only if BS knows the forward channels linking its transmit antennas to these users. Here a time-division duplexed (TDD) broadcast channel is studied with the initial assumption of channel information neither at the BS nor at the users' side. The authors propose two simple transmission strategies, one where users feedback independent of their channel realizations and the other where users feedback based upon their channel realizations. They derive a lower bound on the sum rate which reflects the rate loss compared to a system with perfect channel knowledge and the corresponding approximate sum rate expressions are developed for both schemes. These expressions capture the benefits of channel feedback, multi-user diversity and inter-user interference cancellation, and the cost of exchange of information required, and hence can be optimized for the sum rate maximization.

In a similar vein, [44] considers the case where channel reciprocity is exploited in a time-division duplexed (TDD) broadcast channel. The authors provide a simple transmission strategy, where users feedback independent of their channel realizations and analyze the sum rate of this multi-user system when the channel acquisition load is completely accounted for. They further derive a novel lower bound of the sum rate which allows us to optimize over how many users should inform the BS about their channel information, solving the intriguing trade-off of multiuser diversity, interference cancellation and feedback overhead.

#### **3.2 BER Analysis for Pilot-Assisted Receivers (UCL-UGent, UCL-UGent/CNRS-EURECOM in 2009-2010)**

The work of UCL-UGent considered in 2008 addressed analytical performance of orthogonal space-time block-codes (OSTBCs). This work was extended by joint studies with CNRS-EURECOM. The focus will be on the investigation of channel estimation errors on the BER performance of a MIMO system with precoding and analog feedback of channel state information. This work builds upon the previous results and those of CNRS-EURECOM (See section 4.3). To-date, this joint activity has not yielded any scientific publications, although joint meetings were held.

#### **3.3 Universal Code Design for the MIMO channel (CNRS-EURECOM/FTW-TUWien)**

The joint work in [34] identifies the first general, explicit, and non-random MIMO encoder-decoder structures that guarantee optimality with respect to the diversity-multiplexing tradeoff (DMT), without employing a computationally expensive maximum-likelihood (ML) receiver. Specifically, the work establishes the DMT optimality of a class of regularized lattice decoders, and more importantly the DMT optimality of their lattice-reduction (LR)-aided linear counterparts. The results hold for all channel statistics, for all channel dimensions, and most interestingly, irrespective of the particular lattice-code applied. As a special case, it is established that the LLL-based LR-aided linear implementation of the MMSE-GDFE lattice decoder facilitates DMT optimal decoding of any lattice code at a worst-case complexity that grows at most linearly in the data rate. This represents a fundamental reduction in the decoding complexity when compared to ML decoding whose complexity is generally exponential in rate. The results' generality lends them applicable to a plethora of pertinent communication scenarios such as quasi-static MIMO, MIMO-OFDM, ISI, cooperative-relaying, and MIMO-ARQ channels, in all of which the DMT optimality of the LR-aided linear decoder is guaranteed. The adopted approach yields insight, and motivates further study, into joint transceiver designs with an improved SNR gap to ML decoding.

Currently for the  $n_T \times n_R$  MIMO channel, any explicitly constructed space-time (ST) designs that achieve optimality with respect to the diversity multiplexing tradeoff (DMT) are known to do so only when decoded using maximum likelihood (ML) decoding, which may incur prohibitive decoding complexity. In [35], the authors prove that MMSE regularized lattice decoding, as well as the computationally efficient lattice reduction (LR) aided MMSE decoder, allows for efficient and DMT optimal decoding of any approximately universal lattice based code. The result identifies for the first time an explicitly constructed encoder and a computationally efficient decoder that achieve DMT optimality for all multiplexing gains and all channel dimensions. The results hold irrespective of the fading statistics.

In [36], explicit codes are constructed that achieve the diversity-multiplexing gain tradeoff (DMT) of the cooperative relay channel under the dynamic decode-and-forward protocol for any network size and for all numbers of transmit and receive antennas at the relays. Along the way, we prove that space time codes previously constructed in the literature for the block fading and parallel channels are approximately universal, i.e., they achieve the DMT for any fading distribution. It is shown how approximate universality of these codes leads to the first DMT-optimum code construction for the general, MIMO-OFDM channel.

### **3.4 Applications of Compressed-Sensing Techniques (Technion)**

Applications of compressed sensing as well as estimation theoretical results were furthered in [6]-[9], [23]-[27]. These mathematical problem formulations have significant applications in signal processing and could prove very useful for channel estimation for channels with a limited number of degrees of freedom.

## **4 TR2.2 ONGOING ACTIVITIES IN 2009-2010**

TR2.2 provides both fundamental and experimental results pertaining to two-way communications. To a certain extent, the subjects of TR2.2 and TR2.3 are beginning to converge, since the outputs of TR2.2 are used for transmission strategies considered in TR2.3. We present an overview here of the work carried out mainly by JRAs involving, UPC-CTTC-EURECOM and FTW-TUV.

### **4.1 Differential Feedback in MIMO Channels Based on Geodesic Curves (CTTC/UPC)**

This joint research activity reflected in [29]-[33] is a collaboration between UPC and CTTC in the framework of a PhD thesis, where the thesis advisor belongs to UPC and the PhD student to CTTC. Therefore meetings and discussions are performed on a very frequent basis.

The research is focused on the design of feedback strategies for MIMO communications. In general, these feedback schemes are needed in scenarios where channel reciprocity does not hold and, therefore, a feedback channel with limited capacity has to be used to send the channel state information (CSI) from the receiver to the transmitter. In this sense, proper quantization procedures to be applied to the channel estimates have to be designed.

The fundamental objective of the work developed in this JRA is to design and develop a quantization and feedback algorithm that exploits both the correlation in time present in real channels and the intrinsic geometry of the set of Hermitian positive definite matrices.

The research started by developing a feedback strategy based on these principles for the point-to-point MIMO communications channel. This led to the presentation of a paper at the IEEE ICASSP 2009 conference in Taipei (Taiwan). Further work on the algorithm and its statistical properties led to an article submission to IEEE Transactions on Wireless Communications. A study of the optimization of the trade-off between resources assigned to the feedback link and to the communications link was submitted to the Newcom<sup>++</sup> Special Session at the Mobilight 2010 conference, to be held in Barcelona, May 2010.

The broadcast channel was studied next, and a feedback strategy for the Block Diagonalized broadcast channel was accepted for publication at the IEEE ICC 2010. Future work involves the design of feedback strategies for a multiuser scenario with multiple transmitters and multiple receivers.

### **4.2 Differential Feedback Strategies for MIMO Communication Channels using Measured Real-time Channel Databases (CNRS-EURECOM/CTTC/UPC)**

The joint research activity reflected in [28]-[29] continued the work initiated the previous year and focused on publication of the results and dissemination activities. We studied the performance of a differential feedback scheme for multi-input-multi-output (MIMO) communication systems proposed by some of the researchers in this joint research activity using real channel measurement data. This feedback algorithm is applied to the Gram of the channel matrix exploiting geodesic curves and the intrinsic geometry of positive definite Hermitian matrices.

The performance of different feedback strategies has been evaluated using real data and channel measurements obtained with the Eurecom MIMO OpenAir Sounder (EMOS). Additionally, the impact of the realistic assumption of having a delay in the feedback link has also been studied in terms of a loss of performance in the communication through several simulations.

This study has shown that the differential feedback strategy performs much better than the non-differential strategies in real low mobility channels. However, in high mobility channels the performance is similar. A delay in the feedback channel has an important negative effect

on the performance in high mobility channels while having a negligible impact in the slow-varying cases.

As a result of this JRA, 2 conference papers were published in 2009, at the Joint NEWCOM<sup>++</sup>-ACoRN workshop and at the International ITG Workshop on Smart Antennas. Additionally, the dissemination work consisted in the participation in a demo proposal in the Newcom<sup>++</sup> dissemination day (31st March – Barcelona), under the title: “The Eurecom MIMO Openair Sounder (EMOS)”. Collaborators: CNRS/Eurecom, CTTC, UPC, FTW-VUT.

#### **4.3 Use of Analog Feedback in Two-way Communication (CNRS-EURECOM)**

The study in [48] continues the work of the previous year and presents the joint impact of the numbers of antennas, source-to-channel bandwidth ratio and spatial correlation on the optimum expected end-to-end distortion in an outage-free MIMO system. In particular, based on an analytical expression valid for any SNR, a closed-form expression of the optimum asymptotic expected end-to-end distortion valid for high SNR is derived. It is comprised of the optimum distortion exponent and the multiplicative optimum distortion factor. Demonstrated by the simulation results, the analysis on the joint impact of the optimum distortion exponent and the optimum distortion factor explains the behavior of the optimum expected end-to end distortion varying with the numbers of antennas, source-to-channel bandwidth ratio and spatial correlation. It is also proved that as the correlation tends to zero, the optimum asymptotic expected end-to-end distortion in the setting of correlated channel approaches that in the setting of uncorrelated channel. The results in this paper could be performance objectives for analogue-source transmission systems. To some extent, they are instructive for system design.

#### **4.4 Use of Walsh-code layering for HARQ with minimal-delay (CNRS-EURECOM)**

The new study in [49] concerning the uncertainty of channels and peak power constraint, we give a new practical layering scheme to do reliable transmission. In our scheme, Walsh matrix is employed to do layer-time coding. Regarding columns of a layer-time coding matrix as layers and rows as time, after Walsh layertime coding, interference among layers can be removed or diminished by adding rows up. When there are layers decoded successfully after the previous transmission, only not-yet- decoded layers will be retransmitted. Simulation results show that our Walsh layering scheme with hybrid automatic repeat request (HARQ) performs much better than the traditional single-layer ARQ sequential transmission with respect to average time delay.

## **5 TR2.3 ONGOING ACTIVITIES IN 2009-2010**

TR2.3 is dominated by work of a fundamental nature, although for the most part clear applications in wireless (cellular) networks are defined. It is largely the contribution of TECHNION. An important highlight is the new JRA involving CNRS-SUPELEC and TECHNION, which has already yielded some joint publications in reputable scientific conferences.

Some practical results pertaining to LTE MU-MIMO strategies were initiated in 2009 (see Section 5.3). These will be enriched in 2010 with TR2.2 results to propose practical schemes for MU-MIMO transceivers. Contributions from UPC-CTTC and FTW-TUV will be sought.

### **5.1 Empirical Study of MIMO Precoding Strategies Using Measured Channel Databases (CNRS-EURECOM)**

The two-way measurement setup for precoder performance evaluation and design was reported in the 2009 journal paper [37]. This serves as a basis for further work on the subject in 2010 primarily in the direction of low-complexity transceiver structures and feedback strategies for MU-MIMO with QAM alphabets. This work will be used continued jointly with CTTC/UPC and FTW/TUV in 2010 in relation to the feedback mechanisms studied in TR2.2 (see Sections 4.1, 4.2) with a particular focus on implementation of algorithms for the MIMO-Broadcast channel and use of channel reciprocity for TDD. A target will be the demonstration of TDD-based MU-MIMO downlink on OpenAirInterface.org equipment in 2010. This will serve as a starting point for further study in the FP7 SAMURAI project. The transmission strategies for the demonstrator will rely on the recent results described in Section 5.3 which are directly applicable to LTE and the OpenAirInterface.org radio equipment.

### **5.2 Compound state-dependent channels with non-causal state information available at only the transmitter (CNRS-SUPELEC, Technion)**

The joint work carried out in [12][13][15] investigates the capacity of compound state-dependent channels with non-causal state information available at only the transmitter. A new lower bound on the capacity for this class of channels is derived. The bound is shown to be tight for the case of compound channels with stochastic degraded components, yielding the full characterization of the capacity. These results suggest that it would be interesting to explore the optimality of the bound in general. Specific results are derived for the compound Gaussian Dirty-Paper (GDP) channel. Applications of these results arise in a variety of wireless scenarios as multicast channels, cognitive radio channels and related problems with interference cancellation in presence of imperfect channel knowledge.

### **5.3 Linear Precoders for Multiuser MIMO for QAM constellations and a simplified receiver structure under controlled interference (CNRS-EURECOM)**

The work in [40]-[42] proposes idea of exploiting the discrete constellation alphabets in linear precoding for the downlink of multiuser (MU) MIMO. It is shown that the transmission of controlled interference to the users bears the potential of exploiting the interference structure in improving the error resilience. The authors further propose a linear precoding strategy for the downlink of multiuser MIMO on the idea of controlled interference. However under the controlled interference, intuitive optimal receiver is Maximum Likelihood (ML) detector which would require an exhaustive search of the controlled interferers. It would have exponential search complexity in the number of users and their constellation sizes. The authors further propose in this paper a simplified receiver structure which exploits the

interference structure by ML detection but its complexity is equivalent to that of a receiver that confronts no interference (in two user case). Monte Carlo simulations show the improved performance of the proposed linear precoding strategy relative to the existing linear precoding schemes. The results of this work are directly applicable to the MU-MIMO mode of the LTE downlink and show the benefits of advanced receivers in user terminals.

#### **5.4 Robust Downlink Beamforming Using Covariance Channel State Information (Technion)**

The problem of multiuser downlink beamforming is studied under the assumption that the transmitter has erroneous covariance-based channel state information (CSI). The goal is to minimize the transmit power under the worst-case quality-of-service (QoS) constraints. Previous convex optimization-based solutions to this problem involve several coarse approximations of the original problem. In our proposed solution, such coarse approximations are avoided and an exact representation of the worst-case solution is obtained using Lagrange duality. The so-obtained problem is then converted to a convex form using semidefinite relaxation (SDR). Computer simulations show that the SDR step does not involve any approximation as the resulting solution is always rank-one. Simulation results demonstrate substantial performance improvements over earlier worst-case optimization-based downlink beamforming techniques.

#### **5.5 Cooperative Multicell Zero-Forcing Beamforming in Cellular Downlink Channels (Technion)**

In [3], a multicell cooperative zero-forcing beamforming (ZFBF) scheme combined with a simple user selection procedure is considered for the Wyner cellular downlink channel. The approach is to transmit to the user with the “best” local channel in each cell. The performance of this suboptimal scheme is investigated in terms of the conventional sum-rate scaling law and the sum-rate offset for an increasing number of users per cell. We term this characterization of the sum-rate for large number of users as high-load regime characterization, and point out the similarity of this approach to the standard affine approximation used in the high-signal-to-noise ratio (SNR) regime. It is shown that, under an overall power constraint, the suboptimal cooperative multicell ZFBF scheme achieves the same sum-rate growth rate and slightly degraded offset law, when compared to an optimal scheme deploying joint multicell dirty-paper coding (DPC), asymptotically with the number of users per cell. Moreover, the overall power constraint is shown to ensure in probability, equal per-cell power constraints when the number of users per-cell increases.

#### **5.6 Clustered Local Decoding for Wyner-type Cellular Models (Technion)**

We study the uplink of Wyner-type cellular models featuring short range inter-cell interference. The authors assume that the decoding of the message sent by a given transmitter is done locally, that is using only the signals received at the antennas in its vicinity. The authors derive upper and lower bounds on the achievable rate for a two-dimensional model and for a one-dimensional model with an attenuation parameter. The analysis of our cellular models will rely on rate splitting and genie-aided bounds, originally employed in the framework of the interference channel.

### **5.7 A Cognitive Network with Clustered Decoding (Technion)**

The authors study the uplink of a linear cellular model featuring short range inter-cell interference. Specifically, the authors consider a  $K$ -transmitter/ $K$ -receiver interference network where the signal transmitted by a given transmitter is interfered by the signal sent by the transmitter to its left. The authors assume that each transmitter has side-information consisting of the messages of the  $J_e$  users to its left and the  $J_r$  users to its right, and that each receiver can decode its message using the signals received at its own antenna, at the antennas to its left, and at the  $i$ -antennas to its right. For this setting, the authors characterize the multiplexing gain, i.e., the asymptotic logarithmic growth of the sum-rate capacity at high SNR, and point out interesting duality aspects. The authors also present results on the multiplexing gain of a symmetric version of this network where the signal sent by a given transmitter is interfered by the signals sent by the transmitter to its left and the transmitter to its right.

### **5.8 An MMSE Approach to the Secrecy Capacity of the MIMO Gaussian Wiretap Channel (Technion)**

This paper provides a closed-form expression for the secrecy capacity of the multiple-input multiple-output (MIMO) Gaussian wiretap channel, under a power-covariance constraint. Furthermore, the paper specifies the input covariance matrix required in order to attain the capacity. The proof uses the fundamental relationship between information theory and estimation theory in the Gaussian channel, relating the derivative of the mutual information to the minimum mean-square error (MMSE). The proof provides the missing intuition regarding the existence and construction of an enhanced degraded channel that does not increase the secrecy capacity. The concept of enhancement has been used in a previous proof of the problem. Furthermore, the proof presents methods that can be used in proving other MIMO problems, using this fundamental relationship.

### **5.9 A Vector Generalization of Costa Entropy-Power Inequality and Applications (Technion)**

This paper considers an entropy-power inequality (EPI) of Costa and presents a natural vector generalization with a real positive semidefinite matrix parameter. This new inequality is proved using a perturbation approach via a fundamental relationship between the derivative of mutual information and the minimum mean-square error (MMSE) estimate in linear vector Gaussian channels. As an application, a new extremal entropy inequality is derived from the generalized Costa EPI and then used to establish the secrecy capacity regions of the degraded vector Gaussian broadcast channel with layered confidential messages.

### **5.10 Applications of Large Random Matrices in Wireless Communications (Technion)**

In this paper the authors study the spectrum of certain large random Hermitian Jacobi matrices. These matrices are known to describe certain communication setups. In particular, the authors are interested in an uplink cellular channel which models mobile users experiencing a soft-handoff situation under joint multicell decoding. Considering rather general fading statistics the authors provide a closed-form expression for the per-cell sum-rate of this channel in high signal-to-noise ratio (SNR), when an intra-cell time-division multiple-access (TDMA) protocol is employed. Since the matrices of interest are tridiagonal, their eigenvectors can be considered as sequences with second-order linear recurrence. Reference DR2.3

Therefore, the problem is reduced to the study of the exponential growth of products of two-by-two matrices. For the case where  $K$  users are simultaneously active in each cell, the authors obtain a series of lower and upper bound on the high-SNR power offset of the per-cell sum-rate, which are considerably tighter than previously known bounds.

## 6 CONCLUSIONS

This deliverable presented an overview of the activities pertaining to feedback and imperfect channel estimation and the interplay between the two in the form that were considered in NEWCOM<sup>++</sup> WPR.2. Their relation stems from the fact that feedback of channel state information has become an integral part of modern wireless networks (UMTS-HSDPA, UMTS-LTE, 802.16m), both from the point-of-view of resource scheduling and advanced multi-antenna signal processing and therefore the ability to resolve the channel at the transmitter is ultimately related to what can be estimated at the receiver. Moreover, we strongly believe that the analysis of such systems should be considered in the two-way setting since bandwidth for feedback does not come without a price.

We provided the integration activities with other WPR from the network in addition to an up-to-date description of the three tasks of WPR.2 namely, Imperfect channel estimation (TR2.1), Point-to-point and Point-to-multipoint, Two-Way Channels (TR2.2), and Precoding Techniques for the MIMO Broadcast Channels (TR2.3). Cross-WPR and cross-project integration efforts with platform activities were also described.

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