WP1.1– Performance Limits of Wireless Communications

D11.3
Final report on performance limits of wireless communications

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<thead>
<tr>
<th>Contractual Delivery Date:</th>
<th>October 31, 2015</th>
</tr>
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<tbody>
<tr>
<td>Actual Delivery Date:</td>
<td>November 20, 2015</td>
</tr>
<tr>
<td>Responsible Beneficiary:</td>
<td>CNRS</td>
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<td>AAU, Bilkent, CTTC/UPC, CNIT, CNRS, CNRS/Supelec, CNRS/UniPS, CTTC, IASA, INOV, ULund, TUD, UCL, UOULU, UVigo,</td>
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<tr>
<td>Estimated Person Months:</td>
<td>3</td>
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<tr>
<td>Dissemination Level:</td>
<td>Public</td>
</tr>
<tr>
<td>Nature:</td>
<td>Report</td>
</tr>
<tr>
<td>Version:</td>
<td>1.0</td>
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This document describes results obtained in the N# WP 1.1 on Performance Limits of Wireless Communications during the third year of the NoE.

Keywords: Bounds, Cooperative communication, Heterogeneous Networks, Information theory, Large Dimensional Systems, Non-binary Codes, Polar Codes, Random Matrices, Reconfiguration, Relaying, Ressource allocation, Secrecy, Sparse Bayesian Learning, Spatially-Coupled Codes

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## Version history

<table>
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<th>Issue</th>
<th>Date of Issue</th>
<th>Comments</th>
</tr>
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<tr>
<td>0.1</td>
<td>September 30, 2015</td>
<td>First Draft</td>
</tr>
<tr>
<td>1.0</td>
<td>November 15, 2015</td>
<td>Final version</td>
</tr>
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Executive Summary

Deriving the performance limits of Wireless Communications is a key factor to evaluate the margin of improvement of current and future wireless links and networks, including as much as possible actual constraints in terms of packet size, delay, processing complexity etc.

This workpackage targets the basic tools to evaluate such limits. The main research topics that were addressed in the three years of N# are related to

i) The estimation of the ultimate limits of communications and networking, from the physical layer point of view, with special emphasis on physical layer security, and on capacity of channels with constraints such as limited feedback or time-variation

ii) The optimization of the design of multi-hop networks with a cross-layer approach

iii) The development of capacity-achieving channel codes, either as standalone, or as constituents of turbo-like codes, and provide good decoding algorithms for non-binary codes.

Particular attention has been devoted to issues related to cooperative communications via relays and network modelling, to identify optimal relaying strategies and the relevant ultimate capacity.

Apart from the theoretical developments, efforts have been devoted to inter-track activities. For example, common activities with “Task E” of the WP2.1 have been conducted in order to apply some new strategies in the framework of compressive sensing for propagation channel estimation. Virtual Radio Resource Management were implemented in open-source Linux-based LTE eNodeB in collaboration with WP 2.3. The ability of serving multiple groups or Virtual Network Operators has been added to the platform to evaluate the VRRM model in a real LTE emulator.
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Distribution Level: Public
1. Introduction

1.1. Glossary

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<tr>
<td>AP</td>
<td>Access Point</td>
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<tr>
<td>BFIM</td>
<td>Bayesian-Fisher Information Matrix</td>
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<tr>
<td>BiCE</td>
<td>Bias-Correction Estimator</td>
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<tr>
<td>BM</td>
<td>Basis mismatch</td>
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<tr>
<td>CoSaMP</td>
<td>Compressive Sampling Matching Pursuit</td>
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<tr>
<td>CRB</td>
<td>Cramér-Rao bound</td>
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<td>CS</td>
<td>Compressive Sensing</td>
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<td>DNA</td>
<td>Dynamic Network Architecture</td>
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<tr>
<td>FEC</td>
<td>Forward Error Correcting</td>
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<tr>
<td>FRI</td>
<td>Finite Rate of Innovation</td>
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<tr>
<td>HBL</td>
<td>Hierarchical Bayesian Linear</td>
</tr>
<tr>
<td>ISI</td>
<td>intersymbol interference</td>
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<tr>
<td>LDPC</td>
<td>low-density parity-check</td>
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<tr>
<td>LMMSE</td>
<td>Linear Minimum Mean-Square-Error</td>
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<td>MARC</td>
<td>Multiple Access Relay Channel</td>
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<td>OIA</td>
<td>Open Air Interface</td>
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<tr>
<td>OMP</td>
<td>Orthogonal Matching Pursuit</td>
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<tr>
<td>SC</td>
<td>Spatially-coupled</td>
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<td>UE</td>
<td>User Equipment</td>
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<td>VRRM</td>
<td>Virtual Radio Resource Management</td>
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1.2. List of Joint Research Activities (JRAs)

- Task 1.1.1: Theoretic Limits of Communications and Networks (leader: Romain Couillet (CNRS/SUPELEC))
  - JRA 1.1.1.1: Performance limits of Sparse Bayesian Learning with application to wireless communication systems (Remy Boyer)
  - JRA 1.1.1.2: An Information-Theoretic Perspective of Cooperation and Secrecy in Multi-User Communications (Pablo Piantanida)
  - JRA 1.1.1.3: Communications Performance of Large Dimensional Systems (Romain Couillet)

- Task 1.1.2: Relaying and Resource Allocation in Wireless Networks (leader: Savo Glisic (UOULU))
  - JRA 1.1.2.1: Network coding schemes for relay channels (S. Pfletschinger)
  - JRA 1.1.2.2: Optimization approaches for heterogeneous networks (J. Perez-Romero)
  - JRA 1.1.2.3: Traffic dynamics - routing and topology reconfiguration (P. Mertikopoulos)
  - JRA 1.1.2.4: Applying the information bottleneck method in multi-terminal source coding (Georg Pichler)
• Task 1.1.3: Capacity-reaching channel codes (leader: Erdal Arikan (Bilkent))
  – JRA 1.3.1.1: Spatially coupled codes (M. Lentmaier)
  – JRA 1.3.1.2: Non-binary encoders and decoders (G. Montorsi)
  – JRA 1.3.1.3: Coding for multiterminal communication systems (E. Arikan)

1.3. Description of the Main WP Achievements in the Reporting Period

This section presents the main achievements obtained in the three Tasks. They are then developed in Sections 2, 3, and 4.

1.3.1. JRA 1.1.1.1

Bayesian CRB have been adapted to the Compressed Sensing problem relying on results from large dimensional random matrix theory to characterize these bounds in simple and interpretable terms.

Standard sparsity-based estimators in case of Compressed Sensing with Basis Mismatch (BM) suffer from a saturated estimation accuracy. This problem has been analyzed within the JRA. Common effort with "Task E" of the WP2.1 have been conducted in order to apply some new strategies in the framework of CS for propagation channel estimation.

1.3.2. JRA 1.1.1.2

The importance of a feedback signal in securing wireless communications has been studied from an information-theoretic perspective. Two different approaches are employed in the use of the feedback link: i) an analog approach, ii) a digital approach.

In the analog context, an inner bound of the secrecy capacity has been obtained based on the use of joint source-channel coding. In the digital context, inner and outer bounds have been obtained. For the inner bound, the feedback signal is used to generate a secret key hidden from the eavesdropper. The derivation of an outer bound is for a particular class of channels.

1.3.3. JRA 1.1.1.3

Among the many research results obtained within this JRA, the Multicast Cognitive Interference Channel (CIFC) has been considered, where many secondary users are interested in the same cognitive message. The role that Multiple Description (MD) coding can play under simultaneous transmissions has been investigated.

A cooperative two-user multiaccess channel in which the transmission is controlled by a random state. Both encoders transmit a common message and, one of the encoders also transmits an individual message. We study the capacity region of this communication model for different degrees of availability of the states at the encoders, causally or strictly causally. The results shed more light on the utility of delayed channel state information for increasing the capacity region of state-dependent cooperative multiaccess channels.

1.3.4. JRA 1.1.2.2

In the context of heterogeneous Wi-Fi and cellular networks with Multi-Hop capabilities, work has been done on the optimization of the User Equipment (UE) connectivity with the objective
of minimizing the total transmit power. A previously proposed distributed solution based on Q-
learning has been generalized to consider a network with multiple base stations and in which
the UEs acting as Access Points may be operating with the same or with different frequencies.
Comparison with centralized approach using genetic algorithms has shown the efficiency of
the proposed learning technique.

For the activity related to dynamic network architecture (DNA), a new paradigm in wire-
less network access is considered where certain classes of wireless terminals (PCs or smart
phones) can be turned into an AP any time while connected to the Internet. This creates a DNA
since the number and location of these APs vary in time. Incitatives to reward UE that turn to
AP have been studied to optimize the efficiency of the architecture.

Finally, models for Virtual Radio Resource Management (VRRM) were implemented in Open
Air Interface (OAI), i.e., an open-source Linux-based LTE eNodeB, as inter-track activity. Ability
of serving multiple groups or VNOs (Virtual Network Operators) was added to OAI. The goal is
to evaluate the VRRM model in real LTE emulator. The numeric results were obtained through
set of practical scenarios.

1.3.5. JRA 1.1.2.4

Here, a multi-terminal source coding problem has been considered where two separate en-
coders observe two dependent memoryless processes $X^n$ and $Z^n$, respectively. The encoders’
goal is to find rate-limited functions $f(X^n)$ and $g(Z^n)$ that maximize asymptotically the mutual
information $I(f(X^n); g(Z^n))/n$. Non-trivial inner and outer bounds on the optimal characteri-
zation of the achievable rates have been derived for this problem. This type of result may be
applied in the context of distributed hypothesis testing against independence under communi-
cation constraints.

1.3.6. JRA 1.1.3.1

During this reporting period, it has been shown that partially coupled codes are very well suited
for the block fading channel, the diversity order of the code can be increased, without lowering
the code rate, by simply increasing the coupling parameter (memory) of a SC-LDPC code.

Some effort was also done on spatially coupled code design for flexible rates. An altered
LDPC ensemble construction has been introduced that changes the evolution of degrees over
subsequent incremental redundancy steps in such a way, that the degrees can be kept low to
achieve outstanding performance close to Shannon limit for all rates.

1.3.7. JRA 1.1.3.2

A code design optimization has been proposed over the class of irregular LDPC codes compat-
ible with ADBP decoding and obtained performance results improving by 1 dB those obtained
by employing the more conventional regular LDPC.

A decoding solution for non binary polar codes based on ADBP has been successfully tested
and validated. The solution offers performance similar to the optimal solution with a complexity
that also in this case is independent from the cardinality of the alphabet.
1.3.8. JRA 1.1.3.3

The uplink of linear cellular models featuring short range inter-cell interference has been studied. A $K$-transmitter/$K$-receiver interference networks has been considered where the transmitters lie on a line and the receivers on a parallel line; each receiver opposite its corresponding transmitter. Upper and lower bounds on the multiplexing gain have been provided for these networks. For certain setups the upper and lower bounds coincide: for example for the asymmetric network.

Work has also been done on a method that can translate a standard random-coding existence proof to a concrete polar code construction. Standard typical-set proofs rely on a small set of packing and covering lemmas; unfortunately, such lemmas require pairwise independence among codewords and do not apply to polar codes. In this JRA, a first step in relaxing the pairwise independence requirement has been done to prove a form of packing lemma that applies to a generalized form of polar codes.

An intermediate situation between fully orthogonal channels and fully overlapping channels for the Multiple Access Relay Channel (MARC) has been studied. The intent is to study relaying without requiring additional resources, and minimizing the number of nodes involved in the relaying process. The main achievement is to show that this is allowed thanks to the fact that the transmitted signals are protected by some Forward Error Correcting code and using network coding.

Finally, considering the discrete-time intersymbol interference (ISI) channel model, with additive Gaussian noise and fixed $i.i.d.$ inputs, new simple bounds for the achievable rate are proven, and compared to other known bounds.
2. Task 1.1.1: Detailed Activity and Achieved Results

2.1. JRA 1.1.1.1: Performance limits of Sparse Bayesian Learning with application to wireless communication systems (Rémy Boyer)

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   - Bernard Henry Fleury (Aalborg University)
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   - Sylvie Marcos (CNRS/L2S)

2.1.1. Description of Activity

During the first part of the JRA, analytic forms of the Bayesian CRB for the sparse Bayesian linear model with a deterministic dictionary have been derived and analyzed. Based on this first step, Bayesian CRB have been adapted to the Compressed Sensing (CS) problem. Unlike to the sparse signal theory framework, the dictionary in CS is usually considered as a random matrix of large dimensions. As a consequence, in the second part of the JRA, a particular interest has been dedicated to the analysis of performance estimation for sparse Bayesian linear models with large dictionaries. In this context, R. Couillet leading the JRA 1.1.1.3, has been invited to join this JRA due to his expertise in the field of Random Matrix Theory. An application of interest in the context of the project is to use the presented asymptotic results in the context of finite rate of innovation signal estimation.

The performance estimation for sparse Bayesian models where the parameters of interest follow a hierarchical statistical prior has been studied. This family of priors are used in wireless communication and B.H. Fleury has a strong expertise in this topic. A particular interest has been dedicated to Spherically Invariant Random Process (SIRP) in which M.N. El Korso is a recognized expert.

The sampling of non band-limited signals, usually involved in wireless communication systems, has been a first subject of interest in the context of S. Bernhardt’s PhD thesis. This task involves the collaboration of Y. Eldar which is an expert in sampling theory and CS.
Standard sparsity-based estimators in case of CS with Basis Mismatch (BM) suffer from a saturated estimation accuracy. This problem has been studied in S. Bernhardt's PhD thesis. Common effort with "Task E" of the WP2.1 are now conducted in order to apply some new strategies in the framework of CS for propagation channel estimation.

2.1.2. Relevance with the identified fundamental open issues

An important focus was set on Bayesian learning models, which provide classical bounds (of the Cramér-Rao type) the expression of which is in general not tractable and dictionary dependent. The main achievement consisted in relying on results from large dimensional random matrix theory to characterize these bounds in simple and interpretable terms.

A plethora of different estimation algorithms has been adapted to the Hierarchical Bayesian Linear (HBL) model. But, to the best of our knowledge, there is no general performance analysis of this important problem.

Usually, "good" sampling kernels for non band-limited signals are based on criterion involving only the time-delay parameters. Nevertheless, band-limited signals are not only parametrized by the time-delays but also by the amplitudes. The derivation of optimal sampling kernels leading to good performance tradeoff both in time-delays and amplitudes is an open problem.

In realistic CS scenario, as for instance in Tx-Rx wireless communication systems, the knowledge of the basis representation is often uncertain. This model mismatching leads to the collapse of the performance of standard sparse-based estimators.

2.1.3. Main Results Achieved in the Reporting Period and planned activities

1. CS enables measurement reconstruction by using sampling rates below the Nyquist rate, as long as the amplitude vector of interest is sparse. In \cite{3CLF15}, we first derive and analyze the Bayesian Cramér-Rao Bound (BCRB) for the amplitude vector when the set of indices (the support) of non-zero entries of sparse vector is known. We consider the following context:

- (i) The dictionary is non-stochastic but randomly generated;
- (ii) the number of measurements and the support cardinality grow to infinity in a controlled manner, i.e., the ratio of these quantities converges to a constant;
- (iii) the support is random;
- (iv) the vector of non-zero parameters follow a multidimensional generalized normal distribution.

Using results from random matrix theory, we obtain deterministic approximations of the BCRB in closed form. These approximations can be formulated in a very compact form in low and high Signal to Noise Ratio (SNR) regimes. We provide also a statistical analysis of the variance of the oracle linear minimum mean-square-error (LMMSE) estimator and of its statistical efficiency. Finally, we present results from numerical investigations in the context of non-bandlimited Finite Rate of Innovation (FRI) signal sampling. We show that the performance of the BMSE estimators that are aware of the cardinality of the support, such as OMP and CoSaMP, are in good agreement with the developed lower bounds in the high SNR regime. Conversely, sparse estimators exploiting only the knowledge on the parameter vector and on the noise variance in form of a priori distributions, like LASSO
and BPDN, are not efficient at high SNR. However, at low SNR their BMSE is lower than that of the former estimators and it may be close to the BCRB. In particular, in this JRA, a fundamental misleading interpretation published in [PMT3] has been exposed.

In the same "spirit", a corrected explicit formula for the asymptotic oracle-CRB involved in [BKT09, NBZJ12] is derived in the submitted comment correspondence [BBKT15]. Regarding the original articles, the main result on the existence and the statistical efficiency of an unbiased estimator unaware of the locations of the nonzero elements remain correct but the derivation of its variance, given by the oracle-CRB, is incorrect. As illustrated in this comment correspondence, this erroneous variance was too optimistic and always higher bounded by the noise variance even if the ratio of unknown parameters and measurements is close to one. This produces a fundamental misleading comprehension of the estimation performance limit of sparse signals. The corrected expression solves this issue and its practical usefulness is illustrated.

2. Hierarchical Bayesian Linear (HBL) modeling is now a well established branch of the Bayesian inference. In this JRA, we derive and study estimation performance for the HBL model. Specifically, we consider hierarchical priors on the amplitude parameters and the noise precision. We provide closed-form expressions of the BCRB for

(i) unspecified/general prior and hyper-prior for the amplitude parameters and Gaussian-$\lambda$ noise prior,

(ii) Gaussian-$\lambda$ amplitude prior and Gaussian-$\lambda$ noise prior.

Gaussian-$\lambda$ means that the prior is Gaussian and the hyper-prior follows the distribution $\lambda$. For some specific, but commonly used joint distributions, as for instance the SIRP, the BCRB has a compact closed-form expression and enjoys several interesting properties that are discussed in the paper. Finally, a theoretical analysis of the statistical efficiency of the LMMSE estimator is discussed in the low and high noise variance regimes and for stochastically dominant hyper-parameters. This topic has been submitted in [KBLF15].

3. Sampling a finite stream of filtered pulses violates the bandlimited assumption of the Nyquist-Shannon sampling theory. However, recent low rate sampling schemes have shown that these sparse signals can be sampled with perfect reconstruction at their rate of innovation which is smaller than the Nyquist's rate. To reach this goal in presence of digital/quantization noise, an estimation procedure is needed to estimate the time-delay and the amplitude of each pulse. To assess the quality of any estimator, it is standard to use the CRB which provides a lower bound on the MSE of any estimator. In this work, analytic expressions of the CRB are proposed for an arbitrary number of filtered pulses. Using the orthogonal properties of the kernels and its first-order derivative, an approximated compact expression of the CRB is provided. The choice of the kernel is discussed from the point of view of estimation accuracy. This topic has been submitted in [BBM+15a].

The analysis given in [BBM+15a] has been adapted to the sampling of a finite stream of pulses using the popular Sum of Sincs (SoS) kernel parametrized by a vector of weights. So, we propose a new family of sampling kernel which maximizes the Bayesian-Fisher Information Matrix (BFIM) i.e. the total amount of information about the time-delay and amplitude parameters in the measures. The advantage of the proposed family is that it can be user-adjusted to favor one specific parameter. The variety of the resulting kernel goes from a perfect sinusoid to the Dirichlet kernel [BBM+15b].
4. Dictionary based sparse estimators are based on the matching of continuous parameters of interest to a discretized sampling grid. Generally, the parameters of interest do not lie on this grid and there exists an estimator bias even at high SNR. This is the well-known off-grid problem. In [BBZ+14], we propose and study analytical expressions of the BMSE of dictionary-based biased estimators at high SNR. We also show that this class of estimators is efficient and thus reaches the BCRB at high SNR. The proposed results are illustrated in the context of line spectra analysis and several popular sparse estimators are compared to our closed-form expression of the BMSE. This article has been presented during a special session [BL14].

CS is a promising emerging domain which outperforms the classical limit of the Shannon sampling theory if the measurement vector can be approximated as the linear combination of few basis vectors extracted from a redundant dictionary matrix. Unfortunately, in realistic scenario, the knowledge of this basis or equivalently of the entire dictionary is often uncertain, i.e., corrupted by a BM error. The consequence of the BM problem is that the estimation accuracy in terms of BMSE of popular sparse-based estimators collapses even if the support is perfectly estimated and in the high SNR regime. This saturation effect considerably limits the effective viability of these estimation schemes. In a first part, the BCRB has been derived for CS model with unstructured BM. We show that the BCRB foresees the saturation effect of the estimation accuracy of standard sparse-based estimators as for instance the OMP, CosAMP or the BP. In addition, we provide an approximation of this BMSE threshold.

In the second part and in the context of the structured BM model, a new estimation scheme called Bias-Correction Estimator (BiCE) is proposed and their statistical properties are studied. The BiCE acts as a post-processing estimation layer for any sparse-based estimator and mitigates considerably the BM degradation. Finally, the BiCE (i) is a blind algorithm, i.e., is unaware of the uncorrupted dictionary matrix, (ii) is generic since it can be associated to any sparse-based estimator, (iii) is fast, i.e., the additional computational cost remains low, (iv) has good statistical properties.

To illustrate our results and propositions, the BiCE is applied in the challenging context of the compressive sampling of non-bandlimited impulsive signals. This topic has been submitted in [BBML15a, BBML15b, BBML15c].

The planned activities are listed here.

1. Derivation of the performance for CS in case of sparsely corrupted measurements with
   (i) a Gaussian overcomplete measurement matrix of non-asymptotic sizes;
   (ii) a random support, assuming that each entry is modeled as the product of a continuous random variable and a Bernoulli random variable indicating that the current entry is non-zero with probability $P$ and zero with probability $1 - P$.

2. Extension to the CS philosophy to compressive sampling of multidimensional signals by exploitation of the structure of block-sparse tensor. Indeed, at the era of the big data, CS has been extended to the challenging problem of multidimensional data acquisition. In this context, structured sparsity has been generalized to tensors. This exploratory topic will be conducted with the collaboration of M. Haardt.
3. The estimators and the performance bounds proposed and derived in the context of this JRA will be useful for the MAGELLAN ANR project [1]. Indeed, modern cosmological imagers will be constituted of a largely distributed sensor arrays instead of few parabolic antennas. The amount of data is thus massive and CS in the spatial domain is a promising way to tackle this problem. This project involves the SATIE (ENS-Cachan), the L2S (CNRS, CentraleSupelec, UPS), the LTCI (CNRS, Telecom ParisTech) and the Laboratoire JL Lagrange (OCA/CNRS/UNS).

2.1.4. Publications


11. Magellan project, machine learning for very large arrays in radioastronomy
2.2. JRA 1.1.1.2: An Information-Theoretic Perspective of Cooperation and Secrecy in Multi-User Communications (Pablo Piantanida)

Pablo Piantanida (CentraleSupélec), Germán Bassi (CentraleSupélec), Shlomo Shamai (Technion)

2.2.1. Description of Activity

This JRA analyses the use of a feedback signal in securing wireless communications from an information-theoretic perspective. Two different approaches are employed in the use of the feedback link: i) an analog approach, ii) a digital approach.

On the analog approach, the encoder relies on a “feedback-dependent codebook” that correlates the codewords to be sent with the feedback signal. In this way, the encoder seeks to hide as much as possible the transmitted codewords from the eavesdropper’s observations (e.g. beamforming at the codeword level). We derived an inner bound that is based on the use of joint source-channel coding, which introduces time dependencies between the noisy feedback and the channel inputs through different blocks. The proposed technique proved to be powerful and several previous results for different specific models were recovered. However, its complexity prevented us from acquiring useful insights into the workings of this approach and a new one was envisioned.

On the digital approach, the legitimate users extract common randomness from their respective channel output which they use as a shared secret key. This key encrypts the message at the bit level which provides secrecy as long as the eavesdropper cannot obtain the key. This second inner bound also recovered several results from the literature, and as a side result of this second scheme, we derived an inner bound on secret key agreement for the same channel model.

2.2.2. Relevance with the identified fundamental open issues

Present-day security in wireless networks relies on complex cryptography algorithms and secret keys. This technique is far from infallible, specially if the supposed secret keys are compromised. On the other hand, the theory of physical layer security relies on information-theoretical analyses which assures that the eavesdroppers cannot obtain any meaningful information regardless of their computing power.

Nonetheless, in order to obtain positive secrecy rates, the theory of physical layer security demands different statistical properties for the legitimate user’s and eavesdropper’s channel. This assumption cannot be guaranteed most of the time in wireless settings. The use of a feedback signal may help recreate some virtual asymmetries in the channels which will therefore allow higher secrecy rates.

2.2.3. Main Results Achieved in the Reporting Period and planned activities

Analog use of the feedback signal
Partners: Pablo Piantanida (CentraleSupélec), Germán Bassi (CentraleSupélec), Shlomo Shamai (Technion)

1By physical layer security, we mean any strategy applied at the physical layer which ensures safe transmission of information in the presence of an eavesdropper, without resorting to enciphering at higher layers of the communication protocol stack.
The main contribution of this part is the inner bound based on joint source-channel coding. This inner bound recovered previous results from the literature for different channels and feedback models. Additionally, the Gaussian wiretap channel with noisy feedback was analyzed, and the scheme achieved positive secrecy rates even in unfavorable situations where the eavesdropper experiences a much better channel than the legitimate user. The results were published in [BPS15a, BPS15c].

Digital use of the feedback signal
Partners: Pablo Piantanida (CentraleSupélec), Germán Bassi (CentraleSupélec), Shlomo Shamai (Technion)

In this second part, there are two main contributions: an inner bound where the feedback signal is used to generate a secret key hidden from the eavesdropper, and the derivation of an outer bound for a particular class of channels. As a side result, both inner and outer bounds for the secret key capacity were obtained. The inner bound recovers previous results found in the literature, and thanks to the outer bound, new capacity results were found. Additionally, improved secrecy rates were obtained for the Gaussian wiretap channel with noisy feedback. The results will be published in [BPS15d, BPS15b].

Secret Sharing: An Information Theoretic Approach
Partners: S. Shamai (Technion, Y. Liang, L. Lai and S. Zuo): see [ZLLS15].

A novel information theoretic approach is proposed to solve the secret sharing problem, in which a dealer distributes one or multiple secrets among a set of participants in such a manner that for each secret only qualified sets of users can recover this secret by pooling their shares together while non-qualified sets of users obtain no information about the secret even if they pool their shares together. In contrast to the existing solutions that are mainly based on number theoretic tools, an information theoretic approach is proposed in this paper, which exploits the channel randomness during delivery of shares from the dealer to participants as additional resources to achieve secret sharing requirements. In this way, secret sharing problems can be equivalently reformulated into secure communication problems via wiretap channel models, and can hence be solved by employing powerful information theoretic security techniques. This approach is first demonstrated by a simple problem of sharing one secret, which is shown to be equivalent to a communication problem over a compound wiretap channel. Thus, the lower and upper bounds on the secrecy capacity of the compound channel provide the corresponding bounds on the secret sharing rate, and the secrecy schemes designed for the compound channel provides the secret sharing scheme. The power of the approach is further demonstrated by a more general layered multi-secret sharing problem, which is shown to be equivalent to the degraded broadcast multiple input multiple output (MIMO) channel with layered secrecy and decoding constraints. The secrecy capacity region for the degraded MIMO broadcast channel is characterized, which provides the secret sharing capacity region. Furthermore, the secure encoding scheme that achieves the secrecy capacity region provides an information theoretic scheme for sharing the secrets.

2.2.4. Publications
2. German Bassi, Pablo Piantanida, and Shlomo Shamai. On the Capacity of the Wiretap


2.3. JRA 1.1.1.3: Communications Performance of Large Dimensional Systems

(Romain Couillet)

Shlomo Shamai (Technion—Israel Institute of Technology), Pablo Piantanida (CNRS/Supélec), Meryem Benammar (CNRS/Supélec), Romain Couillet (CNRS/Supélec), Gil Katz (CNRS/Supélec), and Abdellatif Zaidi (CNRS).

2.3.1. Description of Activity

The activity of Task 1.1.1 focuses on estimating the ultimate limits of communications and networking and evidently some of the contributions connect also to Task 1.2.1: “Cooperative Multiuser Communications”. In this JRA, strong cooperation with NEWCOM# partners took place mainly with Prof. Pablo Piantanida (SUPELEC), Dr. Meryem Benammar (SUPELEC), Dr. Romain Couillet (SUPELEC), Mr. Gil Katz (SUPELEC) and Prof. Abdellatif Zaidi of Université Paris-Est Marne-La-Vallée. Technical work of S. Shamai with academic coauthors and students, also done within the framework of N# is also presented.

2.3.2. Selected Contributions

“On Multiple Description Coding for the Multicast Cognitive Interference Channel; and The compound broacast channel”

(joint work with P. Piantanida and M. Benammar): see [BPS14] and [PS15];

We investigate in this work the Multicast Cognitive Interference Channel (CIFC) where many secondary users are interested in the same cognitive message. The focus is on characterizing the role that Multiple Description (MD) coding can play under simultaneous transmissions. Though for the very weak, very strong, and mixed very weak/strong interference regimes, resorting to a Common Description (CD) alone is capacity achieving, in the weak interference regime it becomes crucial to resort to a more evolved coding scheme relying on multiple descriptions that could each accommodate differently the interference experienced at the secondary users. A Gaussian example illustrates this claim and various capacity results are likewise reported. We have also investigated the “2 by 1” two-user Compound Broadcast Channel. We investigate an evolved encoding scheme, based on the use of Multiple Description (MD) coding, where the
source transmits both common and private descriptions to the many channel instances of the same user. We derive the resulting MD inner bound and evaluate it for the compound MISO BC by resorting to a Dirty Paper Code (DPC). The suggested MD coding “strictly” outperforms Common Description (CD) coding and hence, palliates better the effect of channel uncertainty.

“Cooperative Multiple Access Channels with Delayed CSI at Transmitters”
(joint work with Abdellatif Zaidi): see [ZS14b].

We consider a cooperative two-user multiaccess channel in which the transmission is controlled by a random state. Both encoders transmit a common message and, one of the encoders also transmits an individual message. We study the capacity region of this communication model for different degrees of availability of the states at the encoders, causally or strictly causally. In the case in which the states are revealed causally to both encoders but not to the decoder we find an explicit characterization of the capacity region in the discrete memoryless case. In the case in which the states are revealed only strictly causally to both encoders, we establish inner and outer bounds on the capacity region. The outer bound is non-trivial, and has a relatively simple form. It has the advantage of incorporating only one auxiliary random variable. In particular, it suggests that there is none, or at best only little, to gain from having the encoder that transmits both messages also sending an individual description of the state to the receiver, in addition to the compressed version that is sent cooperatively with the other encoder. We then introduce a class of cooperative multiaccess channels with states known strictly causally at both encoders for which the inner and outer bounds agree; and so we characterize the capacity region for this class. We also study the model in which the states are revealed, strictly causally, in an asymmetric manner, to only one encoder. In this case, we characterize the capacity region in certain settings. Throughout the paper, we also discuss a number of examples; and compute the capacity region for some of these examples. The results shed more light on the utility of delayed channel state information for increasing the capacity region of state-dependent cooperative multiaccess channels; and tie with recent progress in this framework.

“Cognitive Wyner Networks with Clustered Decoding,”
(joint work with M. Wigger, A. Lapidoth and N. Levy) see: [LLSW14].

This activity is detailed in Section 4.3

“Multiple Access Channels with Action-Dependent State Information,”
(joint work with H. Permuter and L. Dikstein). see: [DPS15].

This activity is detailed in Section 4.3.

“Single Carrier versus OFDM, and Information Theoretic View,”
(joint work with Y. Carmon, and T. Weissman): see: [CSW15].

We compare the maximum achievable rates in single-carrier and OFDM modulation schemes, under the practical assumptions of i.i.d. finite alphabet inputs and linear ISI with additive Gaussian noise. We show that the Shamai-Laroia approximation serves as a bridge between the two rates – while it is well known that the Shamai-Laroia approximation is essentially always a lower bound on the single-carrier achievable rate, it is revealed to essentially always be an upper bound on the OFDM achievable rate. We apply Information-Estimation relations in order to rigorously establish this result for both general input distributions as well as commonly used PAM and QAM constellations. To this end, novel bounds on MMSE estimation of PAM inputs to a scalar Gaussian channel are derived, which are of standalone interest. Our results show that, under reasonable assumptions, sufficiently optimized single-carrier schemes can offer spectral efficiency superior to that of OFDM, motivating further research of such systems.
“Capacity Bounds for Poisson Interference Channels,”
(joint work with L. Lai and Y. Liang): see: [LLS15].
The Poisson interference channel, which models optical communication systems with multiple transceivers, is investigated. Conditions for the strong interference regime are characterized and the corresponding capacity region is derived, which is the same as that of the compound Poisson multiple access channel with each receiver decoding both messages. For the cases when the strong interference conditions are not satisfied, inner and outer bounds on the capacity region are derived. The inner bound is derived via approximating the Poisson interference channel by a binary interference channel and then evaluating the corresponding Han-Kobayashi region. The outer bounds are obtained via various techniques including noise reduction, genie-aided scheme and degraded broadcast channel conversion. The Poisson Z-interference channel is then studied. The sum rate capacity is obtained when the cross link coefficient is either sufficiently small or sufficiently large.

“Vector Perturbation Precoding for the MIMO Broadcast Channels,”
(joint work with B. Zaidel and Y. Avner): see [AZS15].
Precoding schemes in the framework of vector perturbation (VP) for the multiple-input multiple-output (MIMO) Gaussian broadcast channel (GBC) are investigated. The VP scheme, originally a “one-shot” technique, is generalized to encompass processing over multiple time instances. Using lattice based extended alphabets (“perturbations”), and considering the infinite time-span extension limit, a lower bound on the achievable sum-rate using the generalized VP scheme is analytically obtained. The lower bound is shown to asymptotically achieve the optimum sum-rate in the high signal-to-noise ratio (SNR) regime (both in terms of degrees-of-freedom and power offset), for any number of users and transmit antennas. For the two-users case, it is shown that the lower bound coincides with the sum-capacity for low SNR. The above lower bound is constructively obtained by means of an efficient practically oriented suboptimal transmit energy minimization algorithm, which exhibits a polynomial complexity in the number of users. The proposed precoding scheme demonstrates that the “shaping gain” is achievable for VP schemes, when employing “good” multi-dimensional lattices. It is also shown that the suboptimum algorithm has its merits, even when processing over multiple time instances is not employed. For the $2 \times 2$ MIMO GBC, the VP scheme is generalized further, and an inner bound for the entire achievable rate region is obtained, by which an interesting correspondence is identified with the ultimate capacity region, as obtained by “dirty paper coding” (DPC).

“Information Rate of the ISI Channel: Lower Bounds and Approximations,”
(joint work with Y.Carmon): see [CS15]
We consider the discrete-time intersymbol interference (ISI) channel model, with additive Gaussian noise and fixed i.i.d. inputs. In this setting, we investigate the expression put forth by Shamai and Laroia as a conjectured lower bound for the input-output mutual information after application of a MMSE-DFE receiver. A low-SNR expansion is used to prove that the conjectured bound does not hold under general conditions, and to characterize inputs for which it is particularly ill-suited. One such input is then used to construct a counterexample, indicating that the Shamai-Laroia expression does not always bound even the achievable rate of the channel, thus excluding a natural relaxation of the original conjectured bound. However, this relaxed bound is then shown to hold for any input and ISI channel, when the SNR is sufficiently high. Finally, new simple bounds for the achievable rate are proven, and compared to other known bounds. Information-Estimation relations and estimation-theoretic bounds play a key role in establishing our results.
2.3.3. Publications

Journal Papers


Conference Papers


M. Benammar, P. Piantanida and S. Shamai (Shitz), “Capacity Results for the Multicast Cognitive Interference Channel,” IEEE Information Theory Workshop (ITW2015), April 26–May 1, 2015, Jerusalem, Israel.


S. Shamai, EE Dept., Technion—Israel Institute of Technology, Haifa, Israel: Hot Research Topics in Information Theory with Implications on Current and Future Communications Technology, Fp7 Network of Excellence in Wireless COMmunications NEWCOM# Newsletter 8, December 2014.
3. Task 1.1.2: Detailed Activity and Achieved Results

3.1. JRA 1.1.2.1: Network coding schemes for relay channels (S. Pfletschinger)

This JRA was ended in the second year of N#.

3.2. JRA 1.1.2.2: Optimization approaches for heterogeneous networks (Jordi Pérez-Romero)

Participant researchers and affiliations: Jordi Pérez-Romero (UPC), Juan Sánchez-González (UPC), Ramon Agustí (UPC), Beatriz Lorenzo (Univ. of Vigo), Savo Glisic (OUULU), Sina Khatibi (INOV), Luisa Caeiro (INOV), Luis M. Correia (INOV)

3.2.1. Description of Activity

The general framework for this JRA focuses on heterogeneous networks comprised of multiple technologies such as cellular, wireless local area networks, etc., and including also the possibility of resource virtualization. As described in previous deliverables D11.1 and D11.2, the activity has been organized around the following scenarios.

- Scenario 1: Heterogeneous Wi-Fi and Cellular with Multi-Hop capabilities.
- Scenario 2: Dynamic Network architecture scenario.

3.2.2. Relevance with the identified fundamental open issues

As discussed in deliverable D11.2 this JRA addresses the following fundamental open issues:
(i) Development of novel architectural techniques and optimization approaches for efficiently providing ubiquitous broadband access. (ii) Power efficient optimization of the connectivity criteria in heterogeneous cellular network with D2D capabilities. (iii) Optimization of the resource management in heterogeneous virtual Radio Access Networks. (iv) Economic models for the cooperation between multiple operators.

3.2.3. Main Results Achieved in the Reporting Period and planned activities

The main results and achievements of this activity can be summarized in the following points, which are further detailed in the annexes of section 6:
- Scenario 1: The optimization framework presented in deliverable D11.2 to optimize the User Equipment (UE) connectivity with the objective of minimizing the total transmit power, and the proposed distributed solution based on Q-learning have been generalized to consider a network with multiple base stations and in which the UEs acting as Access Points (APs) may be operating with the same or with different frequencies. Then the proposed approach has been evaluated under different conditions and has been compared against a centralized strategy based on genetic algorithms. Results have revealed that the proposed approach achieves a very similar performance in terms of total transmitted power like the genetic algorithm while exhibiting a much lower computational complexity (e.g. computation time reductions from 90min to 10s have been obtained). The robustness of the proposed approach to operate in dynamic scenarios, where APs and/or UEs move and where the role of APs and UEs changes dynamically, has been also studied.
- Scenario 2: A new paradigm in wireless network access is considered where certain classes of wireless terminals (PCs or smart phones) can be turned into an access point any time while connected to the Internet. This creates a Dynamic Network Architecture (DNA) since the number and location of these access points vary in time. We present a DNA optimization framework to optimize different aspects of this new architecture. First, we optimize the network by choosing the most convenient set of available APs to provide the QoS levels demanded by the users. The utility function considered includes the throughput, delay, power consumption and the cost incurred for having certain number of APs. To exploit the soft capacity provided by the DNA, an economic model is developed to award the users by adding a credit to their bills while acting as APs for other users in their vicinity. This serves as an incentive for the users to efficiently use the network resources. Different options for the pricing mechanism are presented for wired and wireless Internet backhaul. As the change in the terminal's role (from user to AP) can make the system prone to eavesdropping, the user’s requirements in terms of security are also considered in the selection of the AP.

- Scenario 3: The concept of virtualization of radio resources has been presented in deliverable D11.2. In addition, the model for Virtual Radio Resource Management (VRRM) is comprehensively described in D11.2. On the same research path, an extension to the VRRM model is proposed, to consider different approaches for estimating the total network capacity with different channel quality pre-assumptions. The new model is able to estimate the total network capacity increment as the effect of applying the techniques introduced in Scenarios 1 and 2. Based on a set of practical reference scenarios, the performance of the model is evaluated and the numeric results are obtained.

Furthermore, the proposed concept and model of Scenario 3 were implemented in Open Air Interface (OAI), i.e., an open-source Linux-based LTE eNodeB, as inter-track activity. In a first step, the ability of serving multiple groups or VNOs (Virtual Network Operators) was added to OAI by means of various modifications especially in the scheduler. Next, codes and algorithms were developed in order to translate the received policies from VRRM model for the scheduler. At last, the VRRM model was integrated with OAI to provide the virtualization of radio resources. As the result, it is now possible to serve multiple VNOs on the same eNodeB in OAI. The goal is to evaluate the VRRM model in real LTE emulator. The numeric results were obtained through set of practical scenarios.

### 3.2.4. Publications


Communications, July 2015


3.3. **JRA 1.1.2.3: Traffic dynamics - routing and topology reconfiguration (P. Mertikopoulos)**

This JRA was ended in the second year of N#.

3.4. **JRA 1.1.2.4: Applying the information bottleneck method in multi-terminal source coding (Georg Pichler)**

Georg Pichler, Gerald Matz (TU Wien), Pablo Piantanida (CNRS/Supelec)

3.4.1. **Description of Activity**

We deal with a novel multi-terminal source coding problem in Network Information Theory. The goal of this theoretical work is to characterize the achievable region of a source coding problem motivated by clustering algorithms.

3.4.2. **Relevance with the identified fundamental open issues**

We investigated a novel multi-terminal source coding problem motivated by biclustering applications. In this setting, two separate encoders observe two dependent memoryless processes $X^n$ and $Z^n$, respectively. The encoders’ goal is to find rate-limited functions $f(X^n)$ and $g(Z^n)$ that maximize asymptotically the mutual information $I(f(X^n); g(Z^n))/n$.

3.4.3. **Main Results Achieved in the Reporting Period and planned activities**

We derived non-trivial inner and outer bounds on the optimal characterization of the achievable rates for this problem. Applications also arise in the context of distributed hypothesis testing against independence under communication constraints.

We extended our approach to multiple source and showed that the bounds carry over to this case. Furthermore, we extensively studied a binary example to showcase the fundamental properties of our solutions. In doing so, we believe we were able to identify the major obstacles preventing us from obtaining tight bounds.

Additionally we uncovered many interesting connections to variety of other problems in Network Information Theory.

3.4.4. **Publications**


4. Task 1.1.3: Detailed Activity and Achieved Results

4.1. JRA 1.1.3.1: Spatially coupled codes (M. Lentmaier)

Najeeb ul Hassan (TUD), Iryna Andriyanova (CNRS), Michael Lentmaier (ULUND), Walter Nit-zold (TUD)

4.1.1. Description of Activity

This JRA investigates spatially coupled codes in wireless communication scenarios. Two activities from the last deliverable were continued during this reporting period: i) Spatially coupled codes for block-fading channels, ii) Spatially coupled code design for flexible rates.

Regarding activity i), it has been demonstrated that spatially coupled LDPC codes are very well suited for the block fading channel. In particular, it has been discovered that the diversity order of the code can be increased, without lowering the code rate, by simply increasing the coupling parameter (memory) of a SC-LDPC code. This is a big advantage compared to conventional LDPC codes which require a specific code structure in order to exploit code diversity with iterative decoding. We continued the work since the last reporting period by developing a deeper understanding of the mechanisms that allow exploiting code diversity. Our investigations aimed at a systematic design of SC-LDPC codes if some targeted (but arbitrary) diversity order \(d\) is desired.

Regarding activity ii), we have previously introduced a class of nearly-regular SC-LDPC codes for rate-flexible code design. The focus in this reporting period was on addressing the issue of incorporating rate-compatibility into the design of SC-LDPC codes.

4.1.2. Relevance with the identified fundamental open issues

For the block-fading channel, the diversity order of a code is an important parameter that gives the slope of the word error rate of the decoder. However, low-density parity-check (LDPC) codes fail to provide the diversity gains promised by the outage bound without a special structure of the code. An example of such a structure is given by the root-LDPC codes. However, designing root-LDPC codes with diversity order greater than 2 requires codes with rate less than 1/2. The special structure of the codes makes it a complicated task to generate good root-LDPC codes with high diversity (and thus low rate). Rate compatibility, on the other hand, is also a very relevant feature for a practical realization of SC-LDPC codes.

4.1.3. Main Results Achieved in the Reporting Period and planned activities

Spatially Coupled Codes for Block-Fading Channels

Partners: Najeeb ul Hassan (TUD), Iryna Andriyanova (CNRS), Michael Lentmaier (ULUND)

Our main contribution is an algorithm, allowing to start from a \((J, K)\)-regular, uncoupled LDPC ensemble, from which one can recursively build up a protograph-based SC-LDPC ensemble having any target diversity order. The diversity order is achieved assuming a low-complexity iterative decoding algorithm. The increase of \(d\) comes at the cost of increasing the memory constraint (i.e., the coupling parameter) of the SC-LDPC ensemble. The results are accepted for publication at ITW 2015 [HALF15].
Furthermore, the investigations are extended by assuming a mismatch (or offset) between the first bit of a transmission packet and the first bit of a codeword, *i.e.*, a synchronisation offset. The synchronisation offset has a negative impact on the code diversity. A data-allocation scheme for SC-LDPC codes has been proposed that allows to obtain a robustness to the synchronisation offset. The results were published at IEEE BlackSeaCom 2015 [AHLF15].

**Spatially Coupled Code Design for Flexible Rates**

Paterners: Walter Nitzold (TUD), Michael Lentmaier (ULUND)

Spatially-coupled regular ensembles that support rate-compatibility through extension have been proposed in the literature and show very good performance if the node degrees and the coupling width are chosen appropriately. But due to the strict constraint of maintaining a regular degree, there exist certain unfavorable rates that exhibit bad performance and high decoding complexity. We introduce an altered LDPC ensemble construction that changes the evolution of degrees over subsequent incremental redundancy steps in such a way, that the degrees can be kept low to achieve outstanding performance close to Shannon limit for all rates. These ensembles always outperform their regular counterparts at small coupling width. The results were published at ISIT 2015 [NLF15].

4.1.4. Publications


4.2. JRA 1.3.1.2: Non-binary encoders and decoders (G. Montorsi)

Erdal Arikan (Bilkent), Jossy Sayir (UCAM), Guido Masera (CNIT/POLITO), Muhammad Awais (CNIT/POLITO),

4.2.1. Description of Activity

As higher spectral efficiency and throughput targets are set for future communication systems, existing capacity-approaching channel coding schemes need to be developed further to work
under more demanding scenarios. In general, Task 1.1.3 aims to develop capacity-approaching channel codes for diverse set of future application scenarios. The intended work JRA 1.1.3.2 within this task is to consider efficient decoding algorithms (message-passing) for non-binary LDPC and related codes and the design of good class of non binary codes. Non binary codes are a natural choice for systems achieving large spectral efficiencies employing high cardinality modulation sets. Recently considerable steps forward have been made in this field with the introduction of decoding algorithms like the Extended Min Sum (EMS) [DF07] or the Analog-Digital Belief Propagation (ADBP) [Mon12, AMMM14] which are competitive in term of complexity with those of binary codes. These algorithms use messages relative to non binary quantities allowing to easily couple the iterative decoders with non binary detectors that typically are present in receiver for highly bandwidth efficient systems. In this activity, starting from EMS and ADBP solutions, we develop several algorithms achieving different trade-offs between performance and complexity to further improve the efficiency of the non-binary decoding algorithms and to provide design and analysis tools for the correspondent encoders.

### 4.2.2. Relevance with the identified fundamental open issues

Non-binary LDPC codes [MD01, Gal62, SF05] have shown improved performance over binary LDPC codes especially for short-length frames. Even if more complex than the binary case, the decoding of non-binary LDPC codes remains tractable. An iterative decoding based on the sum-product algorithm was proposed by Davey and MacKay in [MD01]. MacKay and Davey introduced a Fast-Fourier-transform (FFT) or Walsh-Hadamard transform (WHT) in the decoding process to reduce computational complexity [MD01]. This contribution was further improved in [BD03], and [DF07] and motivated more research effort for reaching good trade-off between complexity and efficiency [MBH09, HKZ09].

### 4.2.3. Main Results Achieved in the Reporting Period and planned activities

The research activity has been focused on topics related to ADBP and its potential extensions and applications. In the following we report the main results achieved in the reporting period.

- **Code design for ADBP.** A non binary decoder based on ADBP has complexity independent from the cardinality of the non binary alphabet \( M \) and consequently provides a very low complexity decoding solution for non binary codes, turning a drawback for this code class (decoding complexity) into an advantage. On the other side the use of ADBP decoder requires to construct good LDPC codes in a subclass of non-binary LDPC codes that has been seldom investigated. In fact, while in [BB04] it has been proved that this subclass of codes can achieve the capacity, no practical code design methodology is available. We have performed a code design optimization over the class of irregular LDPC codes compatible with ADBP decoding and obtained performance results improving by 1dB those obtained by employing the more conventional regular LDPC.

- **Study of two stage decoding scheme embedding a hard decoding stage and use of ADBP decoding algorithm in this decoding structure.** We have performed an in-depth investigation of this particular code construction, by extending the results introduced in [WFH97] and showed that it offers performance competitive to the more conventional BICM approach with a smaller complexity. Furthermore we showed that the first soft-decoded stage of this scheme is naturally suited for the adoption of a non binary ADBP based decoder.
• **Application of ADBP in the decoding of non binary polar codes.** Polar codes are a class of codes that provably achieve the channel capacity that received a lot of attention in coding literature starting from their introduction [Ari09]. In particular it has been shown that polarization also occurs for a large class of discrete non binary input symmetric channels by employing polar constructions based on non binary alphabets. The decoding of polar code is based on successive interference cancellation and requires to properly process messages according to the “sum” and “repetitions” nodes correspondent to the polarization transformation. A decoding solution for non binary polar codes based on ADBP has been successfully tested and validated. The solution offers performance similar to the optimal solution with a complexity that also in this case is independent from the cardinality of the alphabet.

• **Nonbinary codes for frame synchronization.** An investigation of mixed non-linear and linear non-binary codes for frame synchronisation was conducted. Bounds on the synchronisation and error performance of these techniques were investigated and compared with the classic approach of preamble-based synchronisation and coding de-coupled from synchronisation. The status of this investigation was presented at the Coding and Modulation workshop in Munich where several Task 1.1.3 participants were present and refinements to the approach were proposed and discussed.

• **Decoding sparse superposition codes.** Approximate message passing was investigated as a method to decode sparse superposition codes and found to achieve the capacity of the AWGN channel. The complexity of this decoding technique scales linearly with the size of the design matrix and can be further reduced by using Hadamard design matrices.

4.2.4. Publications


4.3. **JRA 1.3.1.3: Coding for multiterminal communication systems (E. Arikan)**

Leader: Erdal Arikan (BILKENT), Researchers involved: Shlomo Shamai (TECHNION), Saygun Onay (BILKENT), Pierre Duhamel (CNRS), Pablo Plantanida (CNRS/SUPELEC), Abdellatif Zaidi (CNRS), F. Alberge (CNRS/UPSud), Luc Vandendorpe (UCL), Mohieddine El Soussi (UCL).

4.3.1. **Description of Activity**

This JRA comprises two main research subjects.

- Capacity and coding for multiterminal systems
- Secure transmission over networks

The common thread of these subjects is the quest for understanding characteristics of capacity-achieving code constructions in the multiterminal scenarios. One of the methods used for this purpose is the information-estimation paradigm which investigates the basic features of ŠgoodŠ (capacity approaching) codes operating on a Gaussian channel. A second method is
polar coding which has proven very effective in constructing capacity achieving codes for a num-
ber of multiterminal coding scenarios. In addition to these general methods, we employ specific
coding techniques to construct novel coding schemes that can be used in practical cooperative
coding scenarios such as relays and multiple access channels. Under the secure transmission
research theme, we seek to develop physical layer security methods over networks.

The methods investigated in this JRA aim to improve the efficiency of wireless networks
through more advanced signalling and coding techniques. The methods are developed with
an overriding concern for low-complexity and suitability for practical implementation. At the
moment, no joint activity with Track 2 has taken place; however, feasibility studies are underway
for demonstration of relaying techniques developed under this JRA using Track 2 facilities.

4.3.2. Relevance with the identified fundamental open issues

The ultimate goal of this JRA is to design capacity-achieving signalling and coding schemes
in the multi-terminal settings. Thus the work in this JRA lies at the main research frontier in
wireless communications. The methods used in this JRA combine basic tools of multi-user
information theory with models relevant to wireless networks envisioned for present or future
applications. Understanding fundamental principles of good system architectures and design
of low-complexity schemes in accordance with such architectures is the main aim. These aims
are fully consistent with the goals of this Work Package on “Performance Limits in Wireless
Networks.”

4.3.3. Main Results Achieved in the Reporting Period and planned activities

In this part, we list the main results achieved in the reporting period, grouped by main themes
of the task. Details of these achievements are given in the Appendix.

4.3.3.1. Cooperative Multiple Access Channels with Delayed CSI at Transmitters

This inter-JRA activity has been described in Section 2.2

4.3.3.2. Cognitive Wyner Networks with Clustered Decoding

We study the uplink of linear cellular models featuring short range inter-cell interference. This
means, we study a $K$-transmitter/$K$-receiver interference networks where the transmitters lie on
a line and the receivers on a parallel line; each receiver opposite its corresponding transmitter.
We provide upper and lower bounds on the multiplexing gain of these networks, i.e., on the
asymptotic logarithmic growth of the sum-capacity at high SNR. For certain setups our upper
and lower bounds coincide: for example for the asymmetric network.

4.3.3.3. Multiple Access Channels with Action-Dependent State Information

We consider a two-user, state-dependent MAC, in which one of the encoders, called the in-
formed encoder, is allowed to take an action that affects the formation of the channel states.
Two independent messages are to be sent through the channel: a common message known
to both encoders and a private message known only to the informed encoder. In addition, the
informed encoder has access to the sequence of channel states in a non-causal manner. We
derive a single letter characterization of the capacity region for this setting.
4.3.3.4. Information Rate of the ISI Channel: Lower Bounds and Approximations

We consider the discrete-time intersymbol interference (ISI) channel model, with additive Gaussian noise and fixed i.i.d. inputs. In this setting, we investigate the expression put forth by Shamai and Laroia as a conjectured lower bound for the input-output mutual information after application of a MMSE-DFE receiver. A low-SNR expansion is used to prove that the conjectured bound does not hold under general conditions, and to characterize inputs for which it is particularly ill-suited. New simple bounds for the achievable rate are proven, and compared to other known bounds.

4.3.3.5. Packing theorems for codes with constraints

Polar codes have been shown to achieve capacity limits in a wide variety of multi-terminal coding scenarios. This work aims to find a method that can translate a standard random-coding existence proof to a concrete polar code construction. Standard typical-set proofs in information theory rely on a small set of packing and covering lemmas; unfortunately, such lemmas require pairwise independence among codewords. So, these lemmas do not apply to polar codes. Here, we take a first step in relaxing the pairwise independence requirement and prove a form of packing lemma that applies to a generalized form of polar codes.

4.3.3.6. Multiple Access Relay Channel

We study an intermediate situation between fully orthogonal channels and fully overlapping channels for the Multiple Access Relay Channel (MARC), with the following motivation: Consider an uplink situation in a classical wireless communication system where each user has his own orthogonal resource. Assume that the operator is willing to help these users by allowing some idle node (a relay) to relay their signals without impairing the available resources, i.e., without allocating a new channel to the relay. If the initial users do not change their way of transmitting, they do not even need to be aware of this relaying, only the base station will have to adapt its reception algorithm to the new situation. This is the reason why this intermediate situation can be considered as being backwards compatible since users operating in a classical mode will not have to change the algorithms used for transmitting. Obviously, if one idle node is available per initial user, classical relaying with overlapping channel can solve the problem. The interest here is to reduce the number of nodes that are involved in this process, i.e., idle nodes help several users. This can be obtained by allowing the relay to perform network coding. To summarize, our intent is to study relaying without requiring additional resources, and minimizing the number of nodes involved in the relaying process. Our main achievement is to show that this is allowed thanks to the fact that the transmitted signals are protected by some FEC (Forward Error Correcting).

4.3.4. Publications

The following publications were made in the reporting period.

4.3.4.1. Full papers (published or to appear)


4.3.4.2. Conference papers


• M. Benammar, P.Piantanida and S. Shamai (Shitz), "Capacity Results for the Multicast Cognitive Interference Channel," IEEE Information Theory Workshop (ITW2015), April 26-May 1, 2015, Jerusalem, Israel.


• S. Shamai, EE Dept., Technion–Israel Institute of Technology, Haifa, Israel: Hot Research Topics in Information Theory with Implications on Current and Future Communications Technology, Fp7 Network of Excellence in Wireless COMmunications NEWCOM#Newsletter 8, December 2014.
5. General Conclusions and Prospects

Many theoretical results have been obtained during the three years of N# within WP 1.1. Significant efforts have also been done towards applications via inter-Track collaborations, for example, in the framework of compressive sensing for propagation channel estimation, or implementation of virtual radio resource management techniques in a real LTE emulator.

Several future research directions have been identified. Within Task 1.1.1 on Theoretic Limits of Communications and Networks, we trust that advanced Information Theoretic (IT) concepts will impact the very notion of modern communications with emphasis on wireless communication and the way it is conceived. IT has the potential to fundamentally impact on conceptual understanding of communications networks, and the (close-to-optimal) way to combine classical communications and networking aspects in a unified framework. While seemingly IT is considered to be a mature field, most of the exciting and revolutionary theoretic view is at its infancy and yet to come. In the past, implementing relatively complex algorithms was the main hardship, now we lack basic, most demanded, theoretical results in network IT and related mathematical fields. This motivates massive IT research, which will evidently carry almost immediate practical values and implications. Some topics associated in general with WP11 are Interference Alignment, Cooperative Communications, Massive MIMO, Cloud Communications Systems, Physical-layer Information-theoretic Security, IT Joint Network and Physical Layer Aspects...

Focusing on JRA 1.1.1.1, much effort has been dedicated to obtain analytic forms of Bayesian bounds for learning algorithms. A significant work remains to be done to derivation of the performance for compressive sensing techniques in the case of sparsely corrupted measurements. Extensions to compressive sampling of multidimensional signals should also be investigated by exploitation of the structure of block-sparse tensors. Results obtained within this task will be very useful in future collaborative research projects. For example, modern cosmological imagers will be acquired by largely distributed sensor arrays instead of few parabolic antennas. CS in the spatial domain is a promising way to tackle this huge data acquisition problem. The estimators and the performance bounds derived in the context of JRA 1.1.1.1 will be useful for the MAGELLAN project.

Future research directions related to Task 1.1.2 on Relaying and Resource Allocation in Wireless Networks, and more specifically to the activities of JRA 1.1.2.2 include: (i) Extension of the considered framework for optimizing UE connectivity in the heterogeneous Wi-Fi/cellular scenario to include also the optimization of which UEs are more appropriate to act as APs so that the total power is minimized. (ii) Optimization of the transmitted power levels by the APs, assuming that the D2D technology allowed some sort of dynamic power control. (iii) Detailed implementation of the framework for specific D2D technologies such as Wi-Fi direct. (iv) Further elaboration of DNA network topologies to be incorporated in existing networks. (v) Integration of business end technology models in multi-hop cellular networks.

Within Task 1.1.3 on Capacity-reaching channel codes, spatially coupled codes have been proven to achieve the capacity of binary-input memoryless channels with low-complexity iterative decoding. Within Task 1.1.3, different aspects of spatially coupled LDPC codes have been investigated, which are relevant in wireless communication systems: efficient window decoding, code design for flexible rates and performance on block fading channels. But spatial coupling is not limited to LDPC codes. One interesting topic, for example, that was not studied within N# is the combination of spatial coupling with polar coding - two topics that both have been studied individually within the project. Both code constructions provably achieve capacity...
with low complexity coding. The successive cancellation decoding of polar codes is closely connected to message passing algorithms like BP decoding, which are used for spatially coupled codes. But the underlying mechanisms, polarization and threshold saturation, which lead to their excellent asymptotic performance, are different. Up to now it is an open problem to show whether one can take advantage of these mechanisms in a combined way.

Beyond this it is an interesting topic to investigate the effect of spatial coupling in scenarios beyond coding. Iterative algorithms are widely used for improving the performance of communication systems. Different locally operating components of the receiver exchange messages with each other in order to approximate the optimal global solution. The key is that the complexity of such a receiver is still in the order of the individual components, while an optimal receiver would be prohibitively complex. Whenever such an algorithm can be described by means of a graphical model, it is possible to apply the concept of spatial coupling on the corresponding graph. It turns out that the threshold saturation phenomenon and the universality and robustness of spatially coupled systems can be observed for various scenarios. Some examples are mentioned in [LAHF15].
6. Annex I: Detailed Description of Main technical WP Achievements

This appendix provides some detailed description of some of the main technical achievements previously presented. Section 6.1 describes some results on secure communication with noisy feedback. Section 6.2 details results obtained in the three different scenarios addressed within JRA 1.1.2.2, namely (i) Heterogeneous Wi-Fi and Cellular with Multi-Hop capabilities, (ii) Dynamic Network Architecture, and (iii) Radio Resource Management for Virtual Radio Access Networks. Sections 6.3 and 6.4 detail some achievements obtained within JRA 1.1.3.1, on Spatially Coupled Codes for Block-Fading Channels and on Spatially Coupled Code Design for Flexible Rates. Finally, Section 6.5 gives some more details on the achievements of JRA1.1.3.3.

6.1. Detailed Technical Achievements JRA 1.1.1.2: Secure Communication with Noisy Feedback

6.1.1. Introduction

In recent years there has been great interest in the study of the wiretap channel (WTC) \cite{LPS08} as a model for secure communications against eavesdroppers by harnessing the randomness inherently present in the physical medium (see \cite{BEH13} and references therein). In this work, we investigate the problem where a node, Alice, wishes to secretly communicate a message to another node, Bob, in presence of a passive eavesdropper, Eve. Alice can communicate with Bob using a general memoryless channel but Eve is listening this communication through another memoryless channel. In addition, we assume that Alice observes general –may be noisy– outdated feedback which is correlated to the channel outputs of Bob and Eve, referred to as “generalized feedback”.

In the literature, there exist two complementary approaches on the use of the feedback signal. On the first one, Alice and Bob extract common randomness from their respective channel output which they use as a shared secret key. On the second approach, Alice correlates the codewords to be sent with the feedback signal in order to hide as much as possible the transmitted codewords from Eve’s observations. In this work, we present an inner bound on the capacity of the memoryless WTC with generalized feedback. The scheme is based on the secret key approach and is complementary to \cite{BPS15c} which was derived using the other approach. With this new scheme, we show improved results for the Gaussian WTC with noisy feedback with respect to \cite{BPS15c}.

6.1.2. Problem Definition and Main Result

In this work, we consider the wiretap channel with generalized feedback, where a source wants to transmit a message $M_n \in \mathcal{M}_n$ securely to a destination with the aid of a feedback signal while an eavesdropper is present in the channel. The WTC with generalized feedback, depicted in Fig. 1, is modeled as a memoryless channel defined by a conditional probability distribution (PD) $p(yyz|x): \mathcal{X} \mapsto \mathcal{Y} \times \hat{\mathcal{Y}} \times \mathcal{Z}$, where $x \in \mathcal{X}$ is the source’s channel input, $\hat{y} \in \hat{\mathcal{Y}}$ is the feedback signal, and $y \in \mathcal{Y}$ and $z \in \mathcal{Z}$ are the legitimate receiver’s and eavesdropper’s channel outputs, respectively.

Definition 1. A secrecy rate $R$ is said to be achievable for this channel if for every $(\epsilon_n, \epsilon'_n) > 0$ there exists a block length $n, \|M_n\| \geq 2^n(R-\epsilon_n)$, randomized encoder functions $\text{enc}_i: (\mathcal{M}_n \times \hat{\mathcal{Y}}^{n-1}) \mapsto$
Figure 1: Wiretap channel with generalized feedback.

\[ X_i, \text{ and a decoder function } \text{dec} : Y^n \mapsto M_n, \text{ such that} \]
\[ \frac{1}{|M_n|} \sum_{m \in M_n} \Pr \left\{ \text{dec}(Y^n) \neq m | X^n = \{ \text{enc}_i(m, \hat{Y}^{i-1}) \}_{i=1}^n \right\} \leq \epsilon_n, \]
\[ \text{and } I(M^n_n; Z^n) \leq n\epsilon'_n, \]

where \( \epsilon_n \) and \( \epsilon'_n \) are sequences that \( (\epsilon_n, \epsilon'_n) \to 0 \) as \( n \to \infty \).

The secrecy capacity \( C_{sf} \) of the WTC with generalized feedback is the supremum of all achievable secrecy rates.

We are now ready to introduce our main result. Let \( \mathcal{P} \) be the set of all joint probability distributions given by
\[ p(\text{quxyzy}) = p(\text{qu})p(x|u)p(y|z|x)p(t|v)p(v|uxy), \] (1)
and let \( \mathcal{P}' \) be the subset in \( \mathcal{P} \) with \( Q = \emptyset \). For any \( p \in \mathcal{P} \), let \( R_{KG1} \) be the set of all nonnegative rates satisfying:
\[ R_{KG1} \leq I(U; Y) - I(U; Z|Q) - \max \{I(Q; Y), I_{\hat{Y}}\} \]
\[ + I(V; Y|UT) - I(V; Z|UT) - I(U; T|QZ), \] (2a)
\[ R_{KG1} \leq I(U; Y) - \max \{I(Q; Y), I_{\hat{Y}}\}, \] (2b)

where \( I_{\hat{Y}} = I(V; X\hat{Y}|UY) \), whereas, for any \( p' \in \mathcal{P}' \), let \( R_{KG2} \) be the set of all nonnegative rates satisfying:
\[ R_{KG2} \leq I(V; Y|UT) - I(V; Z|UT), \] (3a)
\[ R_{KG2} \leq I(U; Y) - I(V; X\hat{Y}|UY). \] (3b)

**Theorem 1** (KG inner bound). A lower bound on the secrecy capacity of the wiretap channel with generalized feedback is given by the region:
\[ R \leq \max \left\{ \max_{p \in \mathcal{P}} R_{KG1}, \max_{p' \in \mathcal{P}'} R_{KG2} \right\}. \]

**Sketch of Proof.** In this scheme, the transmission is split into several blocks and the transmitted message in each block is encrypted fully \( (R_{KG2}) \) or partially \( (R_{KG1}) \) with a secret key. The codeword \( v^n \) is used to convey a description of the feedback signal \( \hat{y}^n \) from the previous block, and therefore, allows both end users to generate the secret key during transmission. The complete proof can be found in [BPS15e].

**Remark 1.** If we set \( Q = T = V = \emptyset \), we recover the achievable rate of the WTC without feedback.
6.1.3. AWGN Wiretap Channel with Noisy Feedback

Let us consider a Gaussian channel where the encoder has access to a noisy feedback from the legitimate user. The channel can therefore be modeled as

\[ Y_j = X_j + N_j, \quad \hat{Y}_j = Y_j + S_j = X_j + N_j + S_j, \]

where \( Y_j \), \( Z_j \) and \( \hat{Y}_j \) are the legitimate output, the eavesdropper’s observation and the noisy feedback present at the encoder at time \( j \), respectively. Additionally, \( N_j \), \( S_j \) and \( M_j \) are independent Gaussian noises with variances \( \sigma^2_N \), \( \sigma^2_S \), and \( \sigma^2_M \), respectively.

**Theorem 2.** An inner bound on the secrecy capacity for this channel model is given by all nonnegative rates satisfying:

\[
R \leq \max \left\{ \max_{\alpha, \beta \in [0,1]} R_{KG_1}(\alpha, \beta), \max_{\beta \in [0,1]} R_{KG_2}(\beta) \right\}, \tag{4}
\]

where

\[
R_{KG_1}(\alpha, \beta) = C \left[ \frac{\bar{\alpha}\beta S_b}{1 + \beta S_b} \right] - \max \left\{ 0, C \left[ \frac{\bar{\alpha}\beta S_e}{1 + \beta S_e} \right] \right\}, \tag{5a}
\]

\[
R_{KG_2}(\beta) = C \left[ \frac{\sigma^2_N}{\sigma^2_S + \sigma^2_c} \left( 1 + \frac{\bar{\beta} S_b}{1 + \beta S_e} \right) \right], \tag{5b}
\]

\[
\sigma^2_c = \frac{1 + (1 - \alpha) S_b}{\alpha S_b}, \tag{5c}
\]

\[
\sigma^2_c = \frac{1 + \beta S_b}{\bar{\beta} S_b} \left[ \frac{\sigma^2_N}{\sigma^2_S + \sigma^2_N} \left( 1 + \frac{\bar{\beta} S_b}{1 + \beta S_e} \right) \right], \tag{5d}
\]

and \( S_b = P/\sigma^2_N \) and \( S_e = P/\sigma^2_M \) are Bob’s and Eve’s channel SNR, respectively. The variance \( \sigma^2_c \) corresponds to the compression noise used in the auxiliary RV \( V \).

**Proof.** We propose the following choice of input probability distribution for the KG scheme. Given the variables \( Q, U', \) and \( X' \) all independent \( \mathcal{N}(0, 1) \), and \( N_c \sim \mathcal{N}(0, \sigma^2_c) \) independent of the previous RVs, we construct:

\[
U = \sqrt{\alpha} Q + \sqrt{\bar{\alpha}} U', \quad V = \hat{Y} + N_c, \quad X = \sqrt{\beta} P U + \sqrt{\bar{\beta}} P X', \quad T = \emptyset, \tag{6}
\]

where \( \alpha, \beta \in [0,1] \) and \( \bar{\alpha} = 1 - \alpha \). With this choice of variables, the expressions from the bound \( R_{KG_1} \) (2) and \( R_{KG_2} \) (3) become \( R_{KG_1}(\alpha, \beta) \) (5a) and \( R_{KG_2}(\beta) \) (5b). The complete proof is relegated to [BPS15e].

**Discussion** The expression (4) is optimized numerically and the results are shown in Fig. 2. The dashed curves correspond to the rates achieved by the JSCC scheme of [BPS15c]. Thm. 2

---

\footnote{The JSCC inner bound employs a joint source-channel coding technique to correlate the transmitted codeword in a block with the previous messages and feedback sequences, i.e., the second approach mentioned in the introduction.}
Figure 2: Achievable rate by the JSCC and KG scheme for $S_b = 10$dB and different values of $S_e$, with respect to the feedback noise variance. The topmost dashed line is the channel capacity without the eavesdropper.
3], while the solid ones are from the KG scheme of Theorem 2. We see that, for all values of feedback noise variance or eavesdropper’s channel SNR, the KG scheme performs equally or better than the JSCC scheme. The rate of the KG scheme increases faster than the rate of the JSCC scheme for a decreasing feedback noise variance. Moreover, even with increasing quality in the eavesdropper’s channel, the performance of the KG scheme reaches a minimum level, unlike the JSCC scheme that keeps on reducing its rate.

With the proposed input PDs, the KG scheme clearly outperforms the JSCC scheme in the Gaussian WTC with noisy feedback. However, if this result is only due to the particular choice of distributions for each scheme, the numerical analysis, or if actually the KG scheme performs better, cannot be determined. Nonetheless, the simplicity of the KG scheme with respect to the JSCC scheme is a clear advantage that facilitates the optimization of the inner bound.

6.2. Detailed Technical Achievements JRA 1.1.2.2

6.2.1. Scenario 1 Heterogeneous Wi-Fi and Cellular with Multi-Hop capabilities

An optimization framework was presented and evaluated in section 4.5 of D11.2 with the objective to optimize the User Equipment (UE) connectivity by minimizing the total transmitted power. This optimization framework considered a scenario consisting of a macrocell and several UEs that can act as Access Points (APs) and relay traffic to other UEs. This proposed framework has been extended for the case of multiple macrocells. Moreover, this section considers the case where UEs acting as APs may be operating at the same or at different frequencies. On the other hand, the algorithm performance in scenarios with UE or AP mobility and the possibility that UEs may become an AP or vice versa is also studied.

Concerning the extension of the proposed framework for a multi-cell scenario, the approach considers \( J \) macrocell BSs denoted as the set \( \beta = \{ S_1, ..., S_J \} \) with a cellular technology (e.g. LTE or LTE-A), \( K \) UEs acting as APs denoted as the set \( \Lambda = \{ A_1, ..., A_K \} \) and \( N \) UEs not acting as APs denoted as \( U = \{ u_1, ..., u_N \} \). In the following, the UEs of set \( \Lambda \) will be referred to simply as "APs", while those of set \( U \) will be referred to as "UEs". It is assumed that the macrocells and the APs work at different frequency bands (out-of-band relaying). It is also assumed that each AP is connected to the macrocell BS with lowest propagation path loss. Each UE must connect to one BS in the set \( \beta \) or one of the APs in the set \( \Lambda \). This decision is done by means of the distributed Q-learning described in section 4.5 of D11.2.

For the estimation of the intercell interference among the different \( J \) macrocell BSs, the proposed model determines the average received power per Resource Block (RB) measured by a given UE of the signals that come from the different macrocell BSs. This interference depends on the number of RBs used by each macrocell BS. Concerning the interference among the different APs, the model calculates the average interference observed at the UE coming from all the APs that work at the same frequency. This interference depends on the total fraction of time that each AP is active.

The performance evaluation has been done in a multi-cell scenario represented in Figure 1. This scenario considers three macrocells deployed in an area of 1000m x 1000m. Different positions of the UEs and APs will be considered in the simulations, as well as different number of UEs and APs.

6.2.1.1. Comparison of the different strategies in the multi-cell scenario

Figure 2a shows a comparison of the proposed Q-learning approach with respect to the other considered benchmark strategies described in D11.2 (i.e. "All to macro" where UEs al-
ways connect directly to the BS, "random" where the choice of AP/BS is done randomly and the centralised optimisation approach based on a genetic algorithm) in terms of total transmit power as a function of the number of UEs. In this case, the APs work at different frequencies so they do not mutually interfere. As shown, the results observed with the Q-learning methodology with temperature parameter $\tau = 0.01$ and with logarithmic cooling approaches clearly improve the results obtained by the "All to macro" and "random" strategies by significantly reducing the total transmitted power. Moreover, the proposed Q-learning approach with logarithmic cooling provides very similar performance as the genetic algorithm. Although this does not mathematically prove the guaranteed convergence to the optimum solution, because the genetic algorithm could converge to either a global or a local optimum, it actually reveals that the proposed distributed approach is able to achieve a very close performance to a classical optimization approach such as the genetic algorithm, in spite of being much less complex.

In terms of convergence time, it is obtained that, for the multicell scenarios, the Q-learning approach is able to achieve convergence to a specific solution after an average number of 7.3 decisions per UE. This value is slightly higher than the average number of decisions per UE obtained in D11.2 for a smaller scenario with a single macrocell, that was around 2 or 3 decisions per user. In any case, the algorithm provides fast convergence in all the considered scenarios.

In terms of computational complexity it is worth to stress that the simulation of 10000 time steps for the case of $J=3$ BSs, $K=4$ APs and $N=10$ UEs lasts around 10s with the Q-learning approach in a state-of-the-art computer. On the contrary, the same execution of the simulation with the genetic algorithm lasts around 90 minutes. This reflects the dramatic reduction in computational complexity exhibited by the proposed distributed approach.

Figure 2b evaluates the impact of the interference in the D2D links in the case that all APs

![BS, AP and UE locations in the multi-cell scenario. Coordinates are in meters.](image)
Figure 4: (a) Total average transmitted power aggregated for all BSs and APs when increasing the number of UEs $N$ for $K=12$ access points. (b) Total average transmitted power aggregated for all BSs and APs when APs work at the same and at different frequencies.

work at the same frequency. In this case, the interference among the different APs reduce the capacities in the D2D links. This increases the activity for the different APs, which reduces their availability for relaying traffic and, as a consequence, the UEs tend to connect more frequently to the BSs. As a result, the total transmitted power increases with respect to the case where all APs use different frequencies. In any case, power reductions with respect to the reference case where all UEs connect through the BSs are still significant.

The proposed algorithms have been tested for scenarios with higher number of macrocell BSs, APs and UEs. Although these results are not presented here for the sake of brevity, similar results have been obtained, revealing that the proposed approach is able to achieve a significant power reduction in larger scenarios.

6.2.1.2. Influence of mobility and dynamic changes in the role of APs and UEs

This section presents some illustrative results to give an insight of the capability of the proposed Q-learning methodology to adapt to changes in scenarios where UEs and/or APs move and when the role of APs and UEs changes dynamically. In this respect, in the first experiment, we focus on the situation where a moving AP may become available or unavailable to relay traffic for a particular UE. For that purpose we consider the multi-cell scenario with the positions of the BSs, APs and UEs shown in Figure 1. At time $t=2000$ time steps, AP $A_3$ begins to move from its initial position $(200,800)$ following a straight trajectory to the right until reaching the position $(900,800)$ at $t=9000$ time steps. Then, it remains at this position until the end of the simulation at $t=10000$ time steps. All UEs are continuously generating activity periods of average duration 30 time steps without any inactivity period between them. At the beginning of each period the UEs perform the AP/BS selection. APs work at different frequencies.

We focus the analysis on the behavior of UE $u_1$ (see Figure 1). Figure 3a shows the evolution of the selection probability $Pr_{BS}(2,1)$ that $u_1$ connects directly to the BS $S_2$, and the probability $Pr_{AP}(3,1)$ that $u_1$ selects the 2-hop connection $S_2 \rightarrow A_3 \rightarrow u_1$. The rest of selection probabilities $Pr_{BS}(j,1)$ and $Pr_{AP}(k,1)$ are almost zero during the whole simulation and are not
Figure 5: (a) Selection probabilities $P_{BS}(2,1)$ and $P_{AP}(3,1)$ for $u_1$ in the multicell scenario when there is an AP moving. (b) Selection probabilities $P_{BS}(1,5)$, $P_{AP}(1,5)$ and $P_{AP}(5,5)$ for $u_5$ when there are dynamic changes in the role of APs and UEs.

represented in Figure 3a. As shown, at the beginning of the simulation $u_1$ identifies the direct connection to BS $S_2$ as the best option, with a selection probability close to 1. This is a reasonable choice as the closest AP $A_3$ is located far away from this UE. Then, as $A_3$ moves and approaches the position of $u_1$, Figure 3a shows that the probability $P_{AP}(3,1)$ of selecting this AP starts to increase, and approximately at $t=6000$ time steps the connection through AP $A_3$ is identified as the best option. However, as $A_3$ moves further to the right, and goes away from $u_1$ the UE identifies that the direct connection through BS $S_2$ becomes again the best option. This occurs approximately at $t=7500$ time steps, when the AP $A_3$ is located at position (750,800).

The second experiment intends to assess the capability of the proposed approach to deal with dynamic changes in the role of the APs and UEs. For that purpose, we consider the positions of the BSs, APs and UEs shown in Figure 1. At time $t=1000$ time steps, the AP $A_1$ decides to switch off its relaying capabilities so it becomes a UE. Then, later at $t=4000$ time steps, the UE $u_4$ is configured as an AP denoted as $A_5$. These modifications will have effect on the behavior of UE $u_5$, whose selection probabilities are plotted in Figure 3b. It is observed that, at the beginning, the probability $P_{AP}(1,5)$ increases to a value close to 1, meaning that $u_5$ learns to connect through AP $A_1$. Then, when $A_1$ becomes an UE at $t=1000$ time steps, $u_5$ identifies this situation and the probability $P_{BS}(1,5)$ reaches a high value, meaning that the UE has learnt to use the direct connection to BS $S_1$, which becomes the best option as seen in Figure 1. Finally, after $t=4000$ steps, $u_4$ becomes configured as AP $A_5$ and as a result, $u_5$ identifies this new AP as the best connectivity option to receive service, i.e. $P_{AP}(5,5)$ reaches a value close to 1. This experiment reveals the robustness of the proposed approach to adapt to dynamic variations in the operating conditions.

As a third analysis, we consider the scenario of Figure 1 with the APs and BSs located at fixed positions and all the UEs moving during the simulation following random trajectories. At each position update, a UE can move forward, move back, turn left or turn right with the same probability. Like in the previous experiment, UEs generate continuous activity periods with average duration 30 time steps. The mobile speed is such that a UE moves 3m in each activity period. All APs work at different frequencies. For benchmarking purposes, the proposed Q-learning approach is compared to the centralized genetic algorithm described in D11.2 executed ideally every time step, so that it can be considered as an upper performance bound. Figure
Figure 6: Increase of the total transmitted power with respect to the centralized genetic algorithm for the different strategies in the multicell scenario.

Figure 6 presents the total transmitted power increase for the different methodologies with respect to the genetic algorithm. Significant power reductions are achieved by the proposed Q-learning approach with respect to the case when all the UEs are connected to the macrocell BSs. In turn, the difference between the Q-learning approach with logarithmic cooling and the upper bound given by the centralized genetic algorithm is only 7%, which can be considered a quite satisfactory performance. This reveals the robustness of the proposed approach to operate also under dynamic conditions.

6.2.2. Scenario 2 Dynamic Network Architecture

We have extended the work presented in D11.2 section 4.2, and we developed new second order cone programming (SOCP) based algorithms to optimize jointly the access point (AP) selection and the downlink resource allocation in the DNA. Beamforming is used to minimize the mutual interference between the users. The main contribution is in the series of approximations used to convert a mixed integer linear program into its convex approximation problem. The numerical results demonstrate that the linearized AP selection variables remain near integer which means that the convexifying series of approximations does not introduce significant errors while significantly simplifying the optimization algorithm.

The problem of interest is to maximize the system throughput by jointly designing the beamformers and choosing properly APs for each user. For this problem, our contributions include, but not limited to, the following:

1) We first formulate the joint beamformer and user-AP connection design problem by introducing Boolean selection variables. We recall that even for a fixed user/AP connection setup, beamformer design for throughput maximization is an NP-hard problem. For the considered problem, finding an optimal solution is more challenging due to the combinatorial nature. To solve this problem, we consider the continuous relaxation method, where the selection variables are relaxed to be continuous. Unfortunately, even with the relaxation, the resulting problem is still nonconvex. Thus, we resort to the successive convex approximation method to solve this problem. In particular, after some transformations, we arrive at a second order cone program (SOCP) in each iteration of the iterative procedure. Interestingly, the relaxed selection variables are nearly binary after convergence.
2) By viewing the selection problem as searching for a sparse solution of the beamformers, we study the considered problem from another perspective. Instead of introducing binary selection variable as in the first proposed method, we impose some sparsity degree into the beamformer design problem. This method is motivated by current increasing interests in applying compressed sensing to wireless communications. In this area, research works have focused to activate the required number of antennas for proper transmission while forcing the rest of the antennas to sleep. Thus, in antenna selection problems, sparse vectors will define the inactive antennas at a given time. In our sparsity based approach, the connection between user and AP is selected based on the non-zero beamformer vectors. All the beamformers are forced to become zero, if there is no communication between the users and AP while optimizing the resource sharing. This mainly reduces the complexity of the algorithm and our aim is to introduce this model in delay sensitive network, since it achieves fewer throughputs than the previous proposed algorithm.

3) Further, we consider the impact of the channel estimation errors on the obtained throughput. Simulation results have shown the robustness of the algorithm even when there are certain errors in the channel estimation.

4) Finally, the algorithm has been simulated over practical system and proves the throughput efficiency of the joint optimization algorithm over optimization problem based on the pre-defined fixed connection between user and AP. A summary of the results is presented below. More details can be found in [STH+15].

6.2.2.1. Simulation Results

Figure 5a illustrates the convergence of a system with a given channel model for two different initial selection vectors $s_{i,j}^{(0)}$. It can be observed that the same optimal value is achieved by SVJOA (Sparsity vector approach based joint optimization algorithm) disregarding the initialization. Note that at the point X the algorithm changes the selection vector from $s_1$ to $s_2$ in order to obtain the optimal value. Although SJOA does not require such initialization, it depends on the choice of penalty value. However, for a given channel model the convergence time of SJOA is independent of the penalty value as illustrated in Figure 5b. Furthermore, it is observed that the convergence time of SJOA is smaller than the convergence time of SVJOA. The main reason is the lower number of variables and the low computational complexity of the SJOA compared to SVJOA. However, SVJOA achieves a quick convergence within 35 iterations which is recommended for practical applications.

Optimal solutions of SJOA and SVJOA are used in new algorithm to obtain the final rates which are illustrated in Figure 6a. It is observed that the sum rate increases with N for both algorithms. This increment is large when K>N since the user has wide options to select a better AP. When N>K users have to share the AP, and thus increment of rate is reduced. As T and K increase, the users have high chance to find better APs. Therefore, Figure 6a shows that for a given number of users the sum rate is increased by introducing additional APs or transmission antennas. Moreover, SVJOA provides higher rates compared to SJOA (Sparsity based joint optimization algorithm) for a given system.

Figure 6b illustrates the resilience towards channel estimation error. We consider a system with K=5, N=5, T=3 and 1000 channel realizations. If the receiver estimates the actual channel between the AP and user a rate of 15.75kbps is achieved. For any other erroneous estimation, the actual rate deviates from the calculated rate mentioned above. The cumulative density functions (CDF) of the actual rates with channel estimation error are plotted in Figure 6b. Here, the channel is assumed to be affected by additive white Gaussian noise with the mean $\mu$ and the
Figure 7: (a) Convergence property of the SVJOA, (b) Convergence property of the SJOA

Figure 8: (a) Comparison of the two algorithms, (b) CDF of the sum rate for different variance and mean

variance $\sigma$. It is clear that even with estimation errors, using the proposed SVJOA the actual rate does not drop below 12kbps. Furthermore, the average rate is 15.2kbps for all the realizations and the expected rate loss (or gain) is 3%. This indicates that the proposed algorithm maintains its performance over the channel estimation errors.

Further, we extend our work towards the practical implementation. We consider 150m radius cluster with two static APs, three dynamic APs and five users as shown in the Figure 7a. The system assumed to be undergoing through log normal shadowing ($s$), Rayleigh fading ($f$) and path losses ($d$) with factor 3.5. Therefore, we can modify $h$ as $\hat{h}_{pra} = h(f, d, s)$ for the practical channel model.

Figure 7b illustrates the sum rate changes with respect to the number of active dynamic APs. For a given time instant $t$, we assume there will be $m$ number of active dynamic APs where, $m = [0, 3]$. In order to calculate throughput, here we consider two scenarios, 1) Activating $m$ dynamic APs which guaranteed the maximum throughput, and 2) Averaging over all possible configurations. Hereinafter the calculated rates for above two scenarios are denoted by as maximum (max) rate and average (avg) rates respectively. The conventional approach is establishing the connection between user and the AP based on the minimum distance and optimizes the system throughput. The resultant rate for above path loss based approach are denoted as PL(max) and PL(avg) in Figure 7b. When we compare the average rates for both approaches, we can clearly see the gain of our proposed algorithm over conventional model.
Further, in SVJOA approach, there is no considerable deviation among the different configurations when compared with the average value, since we optimize the connection between user and the AP together with throughput. The obtain results for SVJOA under same configuration is shown in the SVJOA (PL max) curve. We can clearly see the average value for SVJOA is also higher than the PL(max). Further, PL and SVJOA approaches achieve the maximum sum rate under different configurations. In PL model AP 5, 3 and 4 should switch on respectively to achieve the highest sum rate and in SVJOA 3, 4 and 5.

Once the capacity is maximized, the next problem that we consider is how to increase its utilization. The problem has been considered on the general network level. In this line, a number of solutions are developed in [SKL+15] and summarized below:

1) A comprehensive business portfolio for multi-operator spectrum management is presented and analyzed. The portfolio consist of the following business models: a) Capacity aggregation- A model; b) Capacity borrowing/leasing- BL model; c) Cognitive networks- C model; d) Partial cognitive networks- PC model; e) Mutually cognitive networks- MC model; f) Asymmetrical spectral aggregation in heterogeneous network- CW model or Symmetrical spectral aggregation in heterogeneous network- CWC model; g) Economic models for BL system with pricing and, h) Economical models for mutual channel BL (MBL) with high resolution pricing. All these models are compared on the basis of spectra utilization factor, representing the average percentage of spectra being used by the operator.

2) A unified analytical model based on queuing theory is presented to quantify the performance of these business plans for voice and data traffic. Probability of user benefit is used to quantify the likelihood that a user is served by another operator while facing call blocking in its own network. Although the model admits general distributions for user arrival and service rates, the closed-form expressions are obtained for exponential inter-arrival and service times.

3) A number of new fine-grained pricing models are incorporated into the system model enabling the analysis of systems’ micro-economics and user dissatisfaction with the service. The pricing schemes adapt automatically to the traffic volume in the system and enable changing the price and user behavior (reneging) at each new user arrival/departure.

4) By introducing an equivalent service rate in a multi-operator system, existing results in
Figure 10: Spectra utilization factor: (a) analytical results (b) analytical/simulation results (c) in cognitive networks.

queuing theory are modified to obtain analytical results in a tractable form.

The results provide two major guidelines for the future use of the spectrum: a) for the regulatory bodies, spectra aggregation is more efficient than the concept of cognitive networks; b) for the network operators, spectrum alliances are a more efficient way to compete with the powerful operators owning larger portions of the spectrum bandwidth.

6.2.2.2. Simulation Results

Spectra utilization factor for the different business models are presented in Figure 8a versus $\rho$. In all examples one can see that the individual management of the spectra is inferior compared to the joint (aggregated) spectra management. This applies for both data and voice applications. One should also notice that A model performs the best. In Figure 8b, the comparison between analytical and simulation results is presented for a number of examples when $\rho_1 = 1$. In Figure 8c, additional details are presented to demonstrate dependency of spectra utilization factor in cognitive networks with respect to parameter $\alpha_p$ which characterizes the quality of channel sampling algorithms used in the system. The results presented in Figure 8c show that even with perfect channel sensing the cognitive system is inferior compared with the joint spectra management. The performance further deteriorates when $\alpha_p$ is reduced. One should keep in mind that in wireless networks with high traffic dynamics keeping $\alpha_p$ close to one might require a significant effort.

Next, in [LKGCB+15] we consider context-awareness to enhance reliability and robustness in cognitive networks. New routing and security-based metrics are defined to measure route robustness in spatial, frequency and temporal domains. Secure throughput, defined as the percentage of traffic not being intercepted in the network, is provided. The resources needed for spectrum trading are then obtained by jointly optimizing secure throughput and trading price. Simulation results show that when there is a traffic imbalance of factor 4 between the primary and secondary networks, 4 channels are needed to achieve 90% link reliability and 99% secure throughput in the secondary network. Besides, when relay reputation varies from 0.5 to 0.9, a 20% variation in the required resources is observed.

6.2.2.3. Simulation Results

In Figure 9, the probability of not being intercepted, $p_{nd}$, is shown versus $w_{min}$ for different availability probabilities $p$. We assumed that there was an eavesdropper in 10% of the sub-
cells and that the observation time was 8 hours per day. We can see that $p_{nd}$ increases with $\rho$ and $w_{min}$ as the delay $\tau$ is lower. Every additional 10% increase in the number of eavesdroppers resulted in an additional 1% decrease in $p_{nd}$. These results are not shown due to space constraints.

In Figure 10a, the throughput and secure throughput are shown versus $p$ for different channel requirements, $w_{R, min}$. We can see that 99% of the traffic was safely transmitted in the 3D domain. If $w_{R, min}$ increased by 2 channels, the throughput decreased by about 15% in average. Besides, as the required $w_{R, min}$ increased, the effects of the availability probability on throughput become negligible.

In Figure 10b, the utility is shown versus $w_{R, min}$. We considered $\tau_{max} = 3.5$. The $w_{R, min}$ values needed to satisfy this requirement are shown along the dash line. We can see that when $p = 0.6$, the maximum utility was obtained for $w_{R, min} = 3$ ($\xi_{min} = 0.87$). If the user requires higher reliability, the utility decreased as the price was higher. For higher $p$ the optimum utility was obtained for $w_{R, min} = 2$ ($\xi_{min} = 0.80$).

6.2.3.1. Extension of Virtual Radio Resource Management Model

Section 4.5 of D11.2 has described the model for management of the virtual radio resources. The proposed model has two key parts, which are the estimation of the available radio resources and the allocation of the resources. On the same research path, an extension to the VRRM model is proposed, to consider different approaches for estimating the total network capacity with different channel quality pre-assumptions. The aforementioned estimation approach does not consider any assumption on the channel quality of the mobile terminals, this approach being referred to as the General (G) one. By adding assumptions about the mobile terminals’ channel quality, three additional approaches for the estimation of network capacity are considered:

1) Optimistic approach (OP): all RRUs are assigned to users with very good channel quality (i.e., high SINR), therefore, it is assumed that the data rate of each RRU satisfies the following inequality:

\[
0.5R_{b,\text{Low}}^{\text{max}} \leq R_{b[Mbps]} \leq R_{b,\text{High}}^{\text{max}}
\]  
(7)

2) Realistic approach (RE): it is assumed that the RRUs of each RAT are divided into two equal groups and that the data rate of the RRU from each of these groups is as follows:

\[
0 \leq R_{b[Mbps]} \leq 0.5R_{b,\text{Max}}^{\text{max}} \quad \text{Low SINR Group}
\]  
(8)

\[
0.5R_{b,\text{Low}}^{\text{max}} \leq R_{b[Mbps]} \leq R_{b,\text{High}}^{\text{max}} \quad \text{High SINR Group}
\]  
(9)

3) Pessimistic approach (PE): it is assumed that all the RRUs in the system are assigned to users with low SINR so that the boundaries are:

\[
0 \leq R_{b[Mbps]} \leq 0.5R_{b,\text{Max}}^{\text{max}}
\]  
(10)

The estimation equation presented in D11.2 can be further developed for these special case studies, where data rate is bounded between high and low values, the conditional PDF of a single RRU in this case being calculated as follows:

\[
p_{\text{Rb}}(R_{b,\text{RAT1}[Mbps]} | R_{b,\text{LOW}[Mbps]} \leq R_{b,\text{RAT1}[Mbps]} \leq R_{b,\text{MAX}[Mbps]}) = \frac{0.46}{e} \sum_{k=0}^{5} a_k (R_{b,\text{RAT1}})^k - \frac{0.46}{e} \sum_{k=0}^{5} a_k (R_{b,\text{LOW}})^k - \frac{0.46}{e} \sum_{k=0}^{5} a_k (R_{b,\text{HIGH}})^k
\]  
(11)

where \( R_{b,\text{Low}} \) is the boundary for the RRU data rate and \( R_{b,\text{High}} \) is the high boundary for the RRU data rate.

One should note that there is a relationship between the various parameters related to the data rate:

\[
0 \leq R_{b,[Mbps]} \leq R_{b,\text{High}[Mbps]} \leq R_{b,\text{Max}[Mbps]}
\]  
(12)

Based on the reference scenario described in D11.2, Figure 11 presents the allocated data rates to VNO GB in conjunction with minimum and maximum guaranteed data rates. As long as these data rates are in the acceptable region (i.e., shown by the solid colour), there is no violation to the SLAs and guaranteed data rates. It is obvious that in optimistic approach up to 600 subscribers, the maximum guaranteed data rate is offered to the VNO.
other approaches, as the number of the subscribers increases the allocated data rate moves toward the minimum level of the guaranteed data rate. However, in the pessimistic approach as the number of subscribers is higher than 1100, violations to minimum guaranteed data rate can be observed. It means that the network capacity in this approach is lower than the total minimum guaranteed data rates. The model has to violate some of the minimum guaranteed data rates. This figure shows the effect of input SINR on resources usage efficiency and quality of offered service to the VNOs.

The allocated data rates to VNO BG and BE are also plotted in Figure 12. Just the same as VNO GB, it can be seen that high data rate is allocated to these VNOs in OP and RL approaches. In these cases, the high input SINR leads to the high network capacity and the model is not only able to serve the minimum guaranteed data rates, but it can serve acceptable data rates to the best effort (and best effort with minimum guaranteed) VNO. In the high load situations, the VNO BG and BE suffer more from resources shortage. The allocation of resources to VNO BE even stops when more than 1100 subscribers under PE approach is considered.
Regarding to the distribution of allocated data rate to VNO GB, Figure 13 illustrates the variation of the capacity assigned to each service class of this VNO in different approaches. It can be seen that the conversational class, the class with the highest service weight, for the OP and RL approaches received the maximum guaranteed data rate. The allocated data rate for general and pessimistic approaches is placed in the acceptable region. Although for high-density situations in PE case, the data rate decreases to minimum guaranteed data rate, services of this class never experience violation of guaranteed data rate. Streaming class, likewise, in this VNO is always served with the data rate higher than minimum guaranteed. Since the maximum guaranteed data rate for this class is too high and it has the second high serving weight, the assigned capacity did not reach the maximum. For interactive and background classes, it is shown that they face violation of minimum guaranteed data rate in PE approach. The violation situation in background class is more severe, since the services did not receive any data rate as the number of subscribers is higher than 1100 subscribers.

Moreover, the allocated data rate to the interactive and background classes of VNO BG and BE is demonstrated respectively in Figure 14 and Figure 15. It can be seen that for the VNO BG the situation is very much similar to VNO GB. The main difference is the high boundary of allocated data rate. VNO BG does not have a maximum guaranteed data rate or high boundary for allocation of data rates. Consequently, when high network capacity is available, e.g., in OP situation, the services of this VNO are served by comparatively higher data rates comparing to VNO GB. As an example to this discussion, consider conversational class on both VNOs. For optimistic approach with 400 subscribers, VNO GB is granted with 100 Mbps where VNO BG
receives 1.3 Gbps. On the other hand, in case of resource shortage, the VNO BG received lower data rates than the VNO GB. For instance, the share of interactive class of VNO BG when there are 1200 subscribers in PE approach is only 386.63 Mbps while the VNO GB is allocated by 907.77 Mbps.

6.2.3.2. Implementation of VRRM and Open Air Interface

In the next step, the concept of virtualisation of radio resources is implemented in Open Air Interface (OAI), a Linux-based software-based LTE eNodeB. This implementation is to demonstrate the download operation of two groups of users, belonging to different VNOs, providing different type of services with pre-defined requirements. For implementing them (i.e., the concept and model), it is assumed that a cloud host with OAI server is available. OAI is used as infrastructure emulator. In addition to OAI servers, a windows-based Virtual Radio Resource Management (VRRM) server is also deployed on the same network domain, as it is shown in Figure 16. These servers are connected through an internal network managed by cloud provider. Hence, it can be assumed that these links can carry information and control signals among servers.

The primary goal is to integrate VRRM server with OAI for realisation of the aforementioned concept. The VRRM server based on information and statics from the infrastructure emulator makes decisions, and issues policies. Figure 17 shows the chosen approach that is to define a bidirectional interface between OAI and VRRM server to:

1) Transfer the scenarios and configurations from OAI to VRRM
2) Send calculated policies from VRRM to OAI
3) Retrieve real-time statistics and information of VNOs from OAI for VRRM
4) Send updated policies from VRRM to OAI

In addition, changes in OAI are applied to support the virtualisation concept. These changes enable OAI to have multiple groups of subscribers, each one representing the subscribers of a VNO. With this approach, it is possible to impose different policies per VNO/group, offering different service quality to terminals according to the VNO/group they belong to, and collecting statistics of operation separately in order to adapt the scheduler to meet the diverse requirements. The following modification on OAI was defined for the implementation:

1) Adding group-based statistics to eNodeB
2) Introducing new set of long-time statistics using the already implemented listing concept
3) Changing the codes to initialise, fill, and use the aforementioned statics
4) Changing the algorithm of MAC scheduler in order to support the groups policies
5) Adding support for bidirectional connection and the required protocols
6) Changing the codes to add the groups’ information into the XML file

6.3. Achievements JRA1.1.3.1-1: Spatially Coupled Codes for Block-Fading Channels

Partners: Najeeb ul Hassan (TUD), Iryna Andriyanova (CNRS), Michael Lentmaier (ULUND)
In the block-fading channel, coded information is transmitted over a finite number of coherence intervals to provide diversity. The diversity order \( d \) of the code is an important parameter that gives the slope of the word error rate (WER) of the decoder. In order to obtain a better trade-off between the decoding latency, decoding complexity and the diversity order \( d \), we propose to use spatially coupled low-density parity-check (SC-LDPC) codes. It was demonstrated in the last reporting period that SC-LDPC codes, decoded using a latency constrained window decoder, have very good performance over the block-fading channel.

Our recent work [HALF15] is devoted to a systematic design of SC-LDPC codes if some targeted (but arbitrary) diversity order \( d \) is required. We a) study which maximum \( d \) is achievable for a given \((J,K)\) SC-LDPC ensemble, and b) propose a protograph-based construction of SC-LDPC codes that can achieve an arbitrary \( d \), at the cost of an increasing value of the coupling width and, thus, of the memory constraint \( m_{cc} \) for the underlying convolutional structure. In order to achieve the points above, an explicit connection between block stopping sets and diversity is established.

As a comparison reference for our codes, root-LDPC block codes are considered [BGiFBZ10]. This is the most known construction of block-codes for non-ergodic channels, which motivated a number of further results in this area [LYAM10, KL13]. However, all the existing constructions are designed for a single specified value of \( d \) (in most of cases \( d = 2 \)), and will not work well if the number of fading coefficients per codeword changes. Furthermore, the boundedness of the root structure, on which they are built on, does not allow to treat an arbitrary \( d \) without blowing up the number of node classes in their multi-edge graph structure.

Let \( d^{IT} \) denote the iterative diversity that can be achieved by means of an iterative decoding algorithm as opposed to optimal maximum-likelihood (ML) decoding. We propose an algorithm for generating a class of codes with increasing diversity order \( d^{IT} \), which can be used to design the protographs for a wide variety of rates and values of \( d \). Table 1 shows the results of the algorithm when applied with multiple initial steps to find the codes with maximum diversity for rate \( R = 1/2, 2/3 \) and \( 3/4 \) with variable node degree 3 and 4. Let us take an example of a variable node degree 3. It can be seen that the designed protographs achieve the maximum diversity of \( d^{IT} = 6 \) for all considered rates. However, as the rate increases from \( 1/2 \) to \( 3/4 \), the required \( m_{cc} \) to achieve diversity order of \( d^{IT} = 6 \) also increases from 9 to 23. One of the main reasons for this is the increase in the number of variable node sets moving from rate \( 1/2 \) to \( 3/4 \).

<table>
<thead>
<tr>
<th>Code</th>
<th>( m_{cc} )</th>
<th>( d^{IT} )</th>
<th>Code</th>
<th>( m_{cc} )</th>
<th>( d^{IT} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3, 6)</td>
<td>9</td>
<td>6</td>
<td>(4, 8)</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>(3, 9)</td>
<td>14</td>
<td>6</td>
<td>(4, 12)</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>(3, 12)</td>
<td>23</td>
<td>6</td>
<td>(4, 16)</td>
<td>27</td>
<td>6</td>
</tr>
</tbody>
</table>

The algorithm recursively generates the protograph for a SC-LDPC code, as illustrated in Table 2 for a (3,6)-regular code. For further details we refer the reader to [HALF15]. Due to the recursive construction procedure the resulting codes perform well for a variety of different fading durations, which makes them robust against variations in the channel conditions.

In [AHLF15] we have investigated the robustness of SC-LDPC codes against a synchronization offset \( \delta \). As shown in Figure 20, the performance for both root-LDPC codes and SC-LDPC codes deteriorates when a constant offset \( \delta \) is introduced. However, while in the root-LDPC case the diversity immediately degrades to 1, it degrades much slower in the SC-LDPC case.
This happens thanks to the convolutional structure of SC-LDPC codes, allowing to obtain a gradual performance degradation. In fact, the amount of degradation depends on the size $W$ of the window decoder and can be further reduced by a larger $W$ at the expense of an increased decoding latency $N \cdot W$.

Figure 20: WER for root-LDPC and SC-LDPC codes with and without offset $\delta$ ($W = 5$ and $N = 1000$).

### Table 2: Decomposition of a (3, 6)-regular code.

<table>
<thead>
<tr>
<th>Step</th>
<th>$m_{cc}$</th>
<th>$d_{rr}$</th>
<th>Component Matrices</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Init. 2</td>
<td>2</td>
<td>$[1, 1][0, 1][1, 1]$</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Split 3</td>
<td>-</td>
<td>$[1, 1][0, 1][0, 1][1, 1]$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Add 4</td>
<td>3</td>
<td>$[1, 1][0, 1][0, 0][1, 0][1, 1]$</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Split 5</td>
<td>-</td>
<td>$[1, 1][0, 1][0, 0][1, 0]$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Add 6</td>
<td>4</td>
<td>$[1, 1][0, 1][0, 0][1, 0][1, 0]$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$[0, 0][0, 1][1, 0]$</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Split -</td>
<td>-</td>
<td>not possible to split</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Add 7</td>
<td>5</td>
<td>$[1, 1][0, 1][0, 0][1, 0]$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$[0, 0][0, 0][0, 1][1, 0]$</td>
<td>-</td>
</tr>
</tbody>
</table>

6.4. Achievements JRA1.1.3.1-2: Spatially Coupled Code Design for Flexible Rates

Partners: Walter Nitzold (TUD), Michael Lentmaier (ULUND)

Rate-compatible spatially-coupled regular LDPC ensembles were first introduced in [SAT11]. The proposed ensemble construction is based on graph extension and can, in principle, achieve every rational rate. Because of threshold saturation, the iterative decoding performance can be
pushed arbitrarily close to the Shannon limit when the node degrees and the coupling width are chosen sufficiently large.

On the other hand, due to the regularity constraints on the overall node degrees, certain rates are only achievable with high degrees. While this is unproblematic in the infinite coupling width regime, at finite and small coupling width the performance is significantly reduced. Additionally, the complexity of ensembles with high variable node degree is higher. The performance loss can only be overcome by increasing the coupling width. This behavior was already pointed out in [NFL14] for regular spatially-coupled LDPC codes and an ensemble with slight irregularity was proposed that yielded performance closer to the Shannon limit together with low complexity. These results were presented in the last reporting period.

In our more recent work [NFL15], we relax the degree regularity constraints of a rate-compatible spatially-coupled LDPC code ensemble as introduced in [SATS11] to counteract the severe variable node degree increase of the regular construction. We use multi-edge type (MET) LDPC code ensembles to model regular rate-compatible LDPC code ensembles as well as a new proposed rate-compatible LDPC code ensemble with an altered degree evolution. In our ensemble construction the check node degree is not kept constant but decreased with every incremental redundancy step to allow for a sub-linear increase of variable node degrees. With this change, the decoding complexity can be reduced and a smaller coupling width for similar performance can also be achieved.

Figure 21 shows the iterative decoding thresholds for the relaxed ensembles Ens A and Ens B from [NFL15], compared to the Shannon limit and the $K = 25$ regular ensemble from [SATS11]. The relaxed ensembles do outperform the original regular rate-compatible ensemble for moderate coupling width $w = 3$ at all rates. Additionally, the decoder complexity is significantly reduced especially for lower rates. We are currently working on some modifications of the presented MET ensembles that further improve the performance and complexity trade-off.

6.5. Detailed Technical Achievements JRA 1.1.3.3

6.5.1. Capacity and coding for multiterminal systems

Partners: S. Shamai (TECHNION), A. Zaidi (CNRS), P. Plantanida (CNRS/SUPELEC)

A two-user state-dependent multiaccess channel is considered in which the states of the

![Diagram](image)

Figure 21: BP thresholds for the relaxed rate-compatible SC-LDPC code ensembles on the BEC channel. Note that $w = 1$ refers to the uncoupled case.
channel are known noncausally to one of the encoders and only strictly causally to the other encoder. Both encoders transmit a common message and, in addition, the encoder that knows the states noncausally transmits an individual message. We find explicit characterizations of the capacity region of this communication model in both discrete memoryless and memoryless Gaussian cases. The publication [ZS14a] was made on this topic. This work will be continued in the next reporting period by considering more general multiterminal cooperation scenarios.


### 6.5.2. Packing under constraints

Partner: E. Arıkan (BILKENT) Packing and covering lemmas are basic building blocks of coding theorems in information theory. Information theory relies on a small number of packing and covering lemmas to prove a vast number of coding theorems for multi-terminal source and channel coding problems. Unfortunately, the packing and covering lemmas used for proving theorems in a clean way rely on joint, or at least pairwise, independence among the codewords. Joint or pairwise independence are too strong assumptions for various practical code ensembles, including those for polar codes. In work done in the reporting period, we proved a packing lemma under less stringent conditions on the code ensemble. The packing and covering lemmas that we developed are applicable to polar codes so that existing proofs based on standard code ensembles can be translated readily to similar proofs for polar codes.

The following publication was made on the subject:


### 6.5.3. Towards a backward compatible relaying scheme

Partners. P. Duhamel (CNRS), F. Alberge (CNRS/UPSud), L. Vandendorpe (UCL), M. El Soussi (UCL)

We studied an intermediate situation between fully orthogonal channels and fully overlapping channels for the Multiple Access Relay Channel (MARC), with the following motivation: Consider an uplink situation in a classical wireless communication system where each user has his own orthogonal resource. Assume that the operator is willing to help these users by allowing some idle node (a relay) to relay their signals without impairing the available resources, i.e. without allocating a new channel to the relay. If the initial users do not change their way of transmitting, they do not even need to be aware of this relaying, only the base station will
have to adapt its reception algorithm to the new situation. This is the reason why this intermediate situation can be considered as being “backwards compatible” since users operating in a classical mode will not have to change the algorithms used for transmitting. Obviously, if one idle node is available per initial user, classical relaying with overlapping channel can solve the problem. In this JRA, we are interested in reducing the number of nodes that are involved in this process, i.e., idle nodes help several users. This can be obtained by allowing the relay to perform network coding. To summarize, our intent is to study relaying without requiring additional resources, and minimizing the number of nodes involved in the relaying process. This is allowed thanks to the fact that the transmitted signals are protected by some FEC (Forward Error Correcting). The results were obtained in the context of block fading channel model, single antenna and half duplex situation. The users protect the transmitted data via LDPC codes of rate 1/3. The figures below depict the block error rate (BER) of non-cooperative scheme, and of the proposed scheme for the same spectral efficiency (in terms of information bits per channel use) and same total power consumption. Fig. 22 shows the BER curves for the case of single user, Fig. 23 shows the BER curves for the case of 2 users, and Fig. 24 shows the BER curves for the case of 3 users. The BERs are taken as functions of $E_b/N_0$ (in dB). It can be seen that the proposed cooperative scheme significantly outperforms the non-cooperative scheme in the SNRs of interest and achieves a larger diversity gain. Also, we can observe in Figure 1 that LDPC code outperforms the RSC code of rate 1/3.

![Figure 22: Single user situation: BER vs $E_b/N_0$.](image-url)
Figure 23: MARC with 2 users: BER vs $E_b/N_0$.

Figure 24: MARC with 3 users: BER vs $E_b/N_0$. 
References

[] Magellan project, machine learning for very large arrays in radioastronomy.


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